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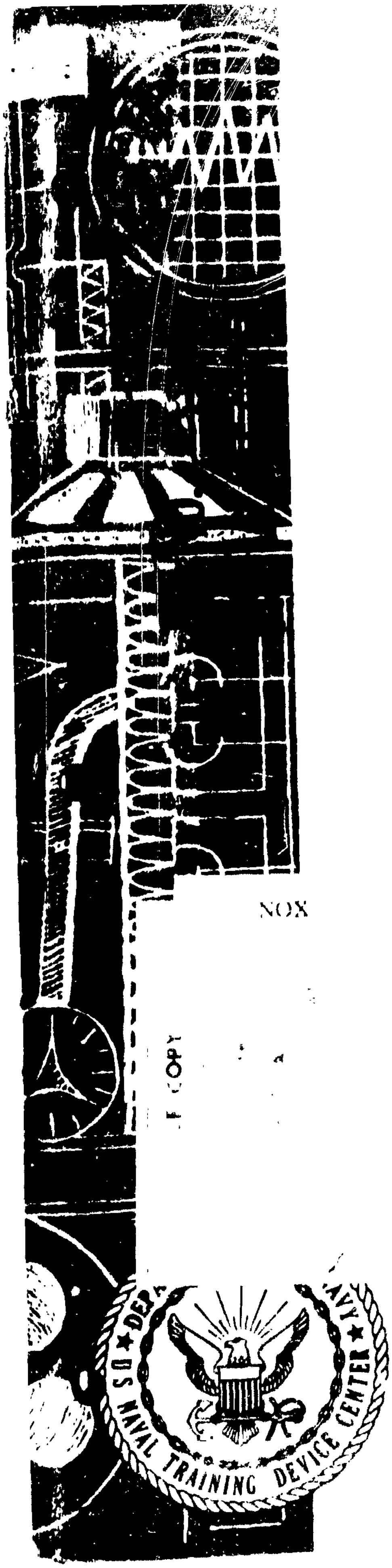

"tools for more effective training"

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TECHNICAL REPORT: NAVTRADEVCEN 1628-1

STUDY OF POINT LIGHT SOURCE PROJECTION SYSTEM COMPONENTS

U.S. NAVAL TRAINING DEVICE CENTER
PORT WASHINGTON, L.I., NEW YORK

Technical Report: NAVTRADEVCEN 1628-1

STUDY OF

POINT LIGHT SOURCE PROJECTION SYSTEM COMPONENTS

Prepared by
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Contract Nonr 1628(00)

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U. S. NAVAL TRAINING DEVICE CENTER
PORT WASHINGTON, NEW YORK

MARCH 1959

Abstract

This report describes the results of a study to evaluate the characteristics of existing point light source projection system components and to develop new components with improved attributes. The components studied are the basic ones involved, namely, the point source of light, the display-object and the screen. Variations in system parameters were studied intensively to determine their inter-relationships and their effects on the qualities of the visual displays obtained. Values of system parameters which achieve optimum visual display qualities were then related to the basic components of the system to establish desirable attributes of these components.

This investigation has advanced the state of the art significantly. The study developed that desirable characteristics of a point light source are a minimum diameter with adequate intensity, a wide horizontal angle of light output and a minimum envelope enclosing the source. A point source of light has been developed with a diameter of .0035 inches, an intensity of 18 candles, a coverage angle in excess of 220° and an envelope .072 inches from the source. This is very close to the theoretical optimum for available lamps. The display-object, which may be transparent or reflective, must be made from a strong, durable material with a high degree of optical clarity and must be decorated to provide realistic content together with sharpness of detail. The best available display-object materials have been determined and display-object decoration techniques have been advanced to permit employment of scale ratios in excess of 2000:1 with satisfactory realism. However, great potential for improvement in point source visual displays lies in the area of display-object decoration. Reflectivity and shape are the important screen factors. A survey of available screen materials revealed that although lenticular screens offer the greatest reflectivity, glass beaded screens are most practicable when complex curved screens are employed. A screen shape which combines a cylindrical surface above the observer's eye level with a segment of a torus shaped surface below eye level was found to minimize the rate of change of position distortion (velocity distortion).

FOREWORD

This report (NAVTRADEVCEN 1628-1) is the first in a series designed to indicate the usefulness of the point-light source in presenting the visual displays required for various training devices. This report presents the current state of the art of point light source projection techniques and indicates areas where further development would contribute most to the usefulness of this technique in training devices. This report describes the major components of the point light source projection system and discusses the parameters involved in selecting these components. Technical considerations in the design of devices using point light source techniques are discussed. Derivation of important relationships as well as other useful technical information are furnished in appendices.

The series of reports consists of:

(1)	NAVTRADEVCEN 1628-1	Study of Point Light Source Projection System Components
(2)	NAVTRADEVCEN 1628-2	Utilization of Point Light Source Techniques in a "Break-out" Landing Attachment to a Twin-Engine Instrument Trainer
(3)	NAVTRADEVCEN 1628-3	The Application of Point Source Projection Techniques to Helicopter Low Altitude Navigation Training
(4)	NAVTRADEVCEN 1628-4	The Application of Point Source Projection Techniques to Low Altitude High Speed Navigation Training
(5)	NAVTRADEVCEN 1628-5	Methods of Presenting Moving Objects in Point-Light Source Visual Displays
(6)	NAVTRADEVCEN 1628-6	The Application of Point Source Projection Techniques to Air-to-Air Gunnery Training
(7)	NAVTRADEVCEN 1628-7	The Application of Point Source Projection Techniques to Air-to-Surface Attack Training
(8)	NAVTRADEVCEN 1628-8	The Application of Point Source Projection Techniques to Air-to-Surface Observation Training

(9)	NAVTRADEVCEN 1628-9	The Application of Point Source Projection Techniques to Surface Vessel Operation Training
(10)	NAVTRADEVCEN 1628-10	The Application of Point Source Projection Techniques to Ground Operation Training
(11)	NAVTRADEVCEN 1628-11	Evaluation of Experimental Light Sources and Transparencies for the Helicopter Hovering Flight Simulation Device 2-FH-2

Each of the reports, NAVTRADEVCEN 1628-2 through 1628-10, discusses the applicability of the point light source system to a specific training problem. Insofar as the point light technique is applicable to that problem, a typical design for a suitable trainer is presented and evaluated. The last report of the series (NAVTRADEVCEN 1628-11) compares two light sources and two transparencies as used on a specific training device. The relative merits of these components are discussed and the importance of various parameters to this training task are evaluated.

Research, experimental work and preparation of the reports were carried out by Edwin K. Smith, Frank J. Anastasio, Sigmund Harac, Berdj C. Kalustyan, Roy B. Snyder and C. Philip Strakosch for the deFlorez Company.

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A	-	Altitude to be simulated, in feet.
A'	-	Minimum altitude to be simulated, in feet.
A''	-	Maximum altitude to be simulated, in feet.
A_R	-	Range of altitude to be simulated, $(A'' - A')$, in feet.
B	-	Luminance of the object of a lens, in candles per square inch.
B'	-	Luminance of the image formed by a lens when the luminance of the object is B, in candles per square inch.
D	-	Display-image width produced by display-object line width J when projected on screen at distance b by extended source S at distance a, in inches.
D'	-	Display-image width produced by display-object line width J when projected on screen at distance b by geometric point source S' at distance a, in inches.
D''	-	Display-image width produced by display-object line width J when projected on screen at distance b by extended source S_1 at distance a, in inches.
D_1	-	Display-image width produced by display-object line width J when projected on screen at distance b by extended source S at distance a_1, in inches.
D_1'	-	Display-image width produced by display-object line width J when projected on screen at distance b by geometric point source S' at distance a', in inches.
D_2	-	Display-image width produced by display-object line width J' when projected on screen at distance b by extended source S at distance a, in inches.

D_2' - Display-image width produced by display-object line width J when projected on screen at distance b by geometric point source S' at distance a", in inches.

D_3 - Display-image width produced by display-object line width J" when projected on screen at distance b by extended source S at distance a, in inches.

F - Luminous flux incident on a lens, in lumens.

F' - Luminous flux transmitted by a lens, in lumens.

G - Width of penumbra on either side of umbra U, (1/2 (D - U)), in inches.

G_1 - Width of penumbra on either side of umbra U_1, in inches.

G" - Width of penumbra on either side of umbra U", in inches.

I - Luminous intensity on object side of lens or lens system, in candles (lumens per steradian).

I' - Luminous intensity on image side of lens or lens system, in candles (lumens per steradian).

J - Width of a line on the display-object, in inches.

J' - Width of any line on the display-object less than J, in inches.

J" - Width of any line on the display-object wider than J, in inches.

M - Theoretical magnification of point source display-object, (D'/J), inches per inch.

M' - Theoretical magnification of point source display-object, at minimum point source to display-object distance a', (D_1'/J), in inches per inch.

M" - Theoretical magnification of point source display-object at maximum point source to display-object distance a", (D_2'/J), in inches per inch.

P	-	Scale ratio, (A/a), in feet per foot.
P_1	-	Ratio of extended source diameter S to display-object line width J, (S/J), in inches per inch.
P'	-	Enlargement of the display-image occasioned by use of extended source S rather than a geometric point source S', (D/D'), in inches per inch.
P"	-	Ratio of the width of umbra to the total display-image width projected by extended source S, (U/D), in inches per inch.
R	-	Radius of any refracting spherical surface, in inches.
R_1	-	Radius of the first surface of a lens, in inches.
R_2	-	Radius of the second surface of a lens, in inches.
S	-	Extended "point source" diameter, in inches.
S'	-	Geometric point source of light (diameter of S' is O).
S_1	-	Any extended "point source" diameter greater than S, in inches.
U	-	Width of umbra of display-image D, in inches.
U_1	-	Width of umbra of display-image D_1, in inches.
U"	-	Width of umbra of display-image D", in inches.
U_2	-	Width of umbra of display-image D_2, in inches.
U_3	-	Width of umbra of display-image D_3, in inches.
X, Y,Z	-	Arbitrary variables, introduced for mathematical convenience and defined to suit particular requirements in each instance.

a	-	Distance from point source to display-object, in feet.
a'	-	Minimum distance from point source to display-object, in feet.
a''	-	Maximum distance from point source to display-object, in feet.
a_R	-	Range of distances from point source to display-object ($a'' - a'$), in feet.
a_1	-	Any distance from point source to display-object greater than a, in feet.
b	-	Distance from display-object to display-image, in feet.
d	-	Distance from point source to screen, in feet.
h	-	Horizontal displacement of eye from point source, in feet.
i	-	Angle of incidence of light on a reflecting or refracting surface, in degrees.
i_1	-	The angle at which a ray at slope angle θ_1, is incident on the first surface of a lens, in degrees.
i_2	-	The angle at which a ray refracted by the first surface of a lens at angle r_1, is incident on the second surface, in degrees.
m	-	Lateral magnification by refractive surfaces, in inches per inch.
m_1	-	Lateral magnification due to the first surface of a lens, in inches per inch.
m_2	-	Lateral magnification due to the second surface of a lens, in inches per inch.
m_L	-	Total lateral magnification of a lens, ($m_1 m_2$), in inches per inch.

n	-	Index of refraction of any medium.
n'	-	Index of refraction of any other medium.
n_1	-	Index of refraction of air $(n_1 - 1)$.
n_2	-	Index of refraction of glass.
r	-	Angle of refraction of light emerging from a refractive surface, in degrees.
r_1	-	The angle at which a ray incident on the first surface of a lens at angle i_1 is refracted by that surface, in degrees.
r_2	-	The angle at which a ray incident on the second surface of a lens at angle i_2 is refracted by that surface, in degrees.
s	-	The distance measured along the optical axis from the object of a refracting surface to that surface, in inches.
s'	-	The distance measured along the optical axis from a refracting surface to the image formed by that surface, in inches.
s_1	-	The object distance of a lens; the distance measured along the optical axis from the object of the first surface to the first surface, in inches.
s_1'	-	The distance measured along the optical axis from the first surface to the image formed by that surface when the object is at distance s_1, in inches.
s_2	-	The distance from the object of the second surface (this is the image of the first surface) to the second surface, in inches.
s_2'	-	The image distance of a lens; the distance measured along the optical axis from the second surface to the image formed by that surface when the object is at distance s_2, in inches.

t	-	Thickness of a lens at the optical axis, in inches.
v	-	Vertical displacement of eye from point source, in feet.
α	-	Extended source angle, in degrees.
β	-	The angle with its vertex at the eye of the observer subtended by the edges of a detail on the display-image in degrees.
γ	-	Diffraction angle, in degrees.
δ	-	Viewing angle, in degrees.
δ_1	-	The viewing angle toward the top of a detail on the display-image, in degrees.
δ_2	-	The viewing angle toward the bottom of a detail on the display-image when δ_1 is the viewing angle to the top of that detail, in degrees.
$\Delta\delta$	-	The angle at the eye subtended by the line of sight at viewing angle δ_2 and the line of sight at viewing angle δ_1, $(\delta_2 - \delta_1)$, in degrees.
ζ	-	Projection angle, in degrees.
ζ_1	-	The projection angle toward the top of the detail on the display-image which is viewed at angle δ_1 in degrees.
ζ_2	-	The projection angle toward the bottom of the detail on the display-image which is viewed at angle δ_2 in degrees.
$\Delta\zeta$	-	The angle at the point source subtended by the line of projection at projection angle ζ_2 and the line of projection at projection angle ζ_1, $(\zeta_2 - \zeta_1)$, in degrees.
η	-	Position distortion, $(\zeta - \delta)$, in degrees.

η_1 - Position distortion, $(\zeta_1 - \delta_1)$, in degrees.

η_2 - Position distortion, $(\zeta_2 - \delta_2)$, in degrees.

$\Delta\eta$ - Size distortion, $(\Delta\zeta - \Delta\delta)$, in degrees.

θ - Slope angle of any ray on the object side of a lens, in degrees.

θ_1 - The slope angle of any ray incident on the first surface of a lens, in degrees.

θ_2 - The slope angle of a ray incident on the second surface of a lens when the ray is incident at angle θ_1 on the first surface, in degrees.

θ' - The slope angle after refraction by a lens system of the ray which has slope angle θ before refraction, in degrees.

θ_1' - The slope angle after refraction by the first surface of a lens of the ray which has slope angle θ_1 before refraction, in degrees.

θ_2' - The slope angle after refraction by the second surface of a lens of the ray which has slope angle θ_2 before refraction, in degrees.

λ - The wavelength of light.

ϕ - The entrance half angle. This is the limiting value of θ for a specified aperture, in degrees.

ϕ' - The exit half angle when the entrance half angle is ϕ, in degrees

ω - The entrance solid angle when the entrance plane angle is 2ϕ, in ste ..ians.

ω' - The exit solid angle when the exit plane angle is $2\phi'$, in steradians.

Γ_L - Total longitudinal magnification of a lens, $(- (m_L)^2)$, in inches per inch.

Sign Conventions in the Point Source System

1. Vertical displacement of the eye from the point source - positive when the point source is above the level of the eye and negative when the point source is below the level of the eye.

2. Horizontal displacement of the eye from the point source - positive when the point source is behind the observer and negative when the point source is in front of the observer as the observer faces the screen.

3. Projection angle - positive when the line of projection is downward from the point source and negative when the line of projection is upward from the point source.

4. Viewing angle - positive when the line of sight is downward from the observer's eye and negative when the line of sight is upward from the observer's eye.

5. Position distortion - positive when the projection angle is algebraically greater than the viewing angle. Since the other distortions are derived from position distortion, their sign conventions are similarly derived.

Sign Conventions in Optics

1. All figures are drawn with the light incident on the reflecting or refracting surface from the left.

2. The object distance is positive when the object is at the left of the vortex of the surface in question. (the vertex of a refracting surface is the point where the surface crosses the optical axis).

3. The image distance is positive when the image is at the right of the vertex of the surface in question.

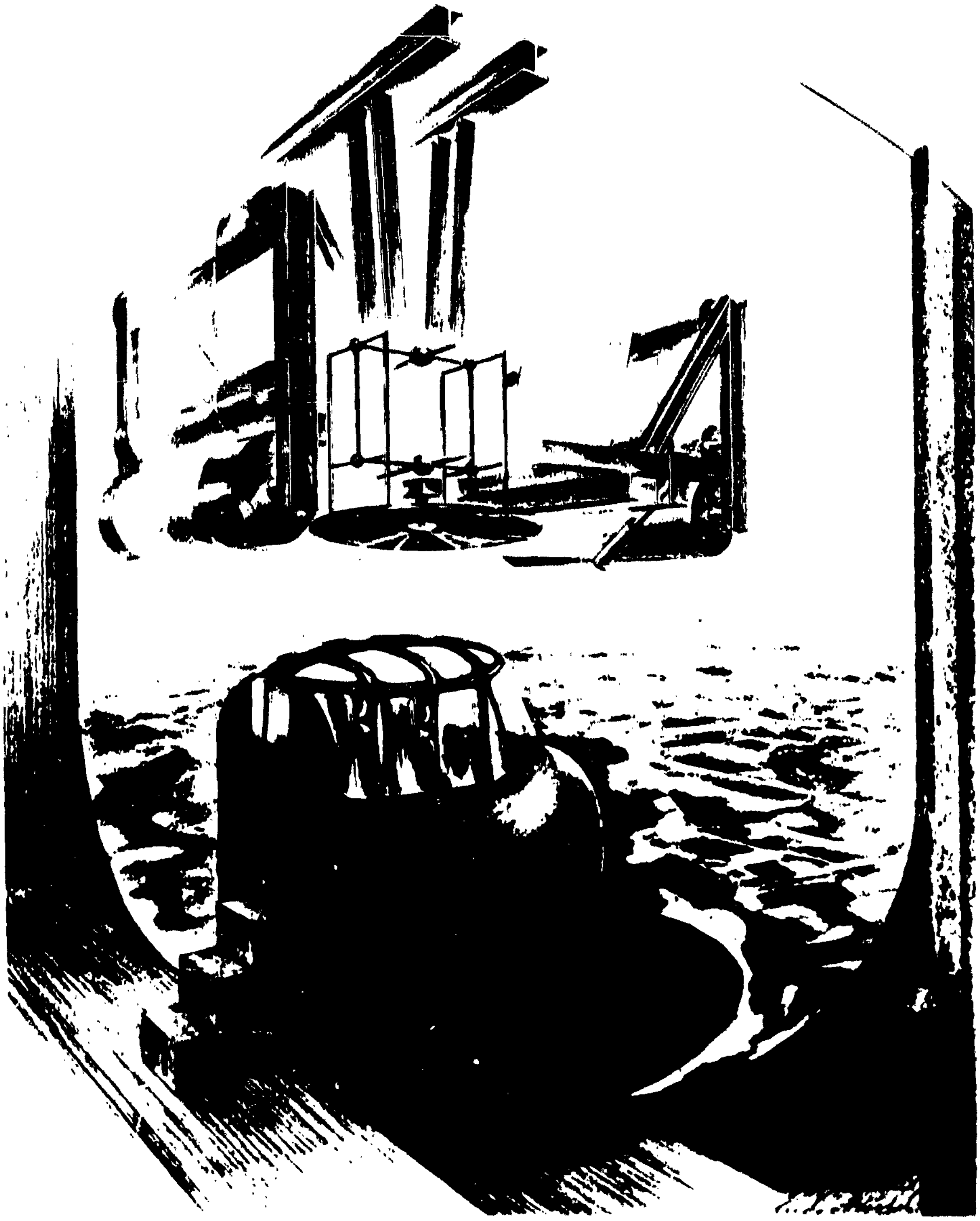
4. The radius of curvature is positive when the center of curvature lies at the right of the vertex of the surface in question.

5. The slope angles are positive when the axis must be rotated counter clockwise through less than $\pi/2$ to bring it into coincidence with the ray.

6. The angles of incidence and refraction are positive when the radius of curvature must be rotated counter-clockwise through less than $\pi/2$ to bring it into coincidence with the ray.

7. Distances perpendicular to the optical axis are positive when measured upward from the axis.

8. Positive lateral magnification indicates that the image is erect while negative lateral magnification indicates that the image is inverted.



Frontispiece - An Artist's Concept of a Typical Point Source Projection System (Device 2-FH-5)

CHAPTER 1

Introduction to the Point Light Source Projection System and Its Components

1.1 Introduction

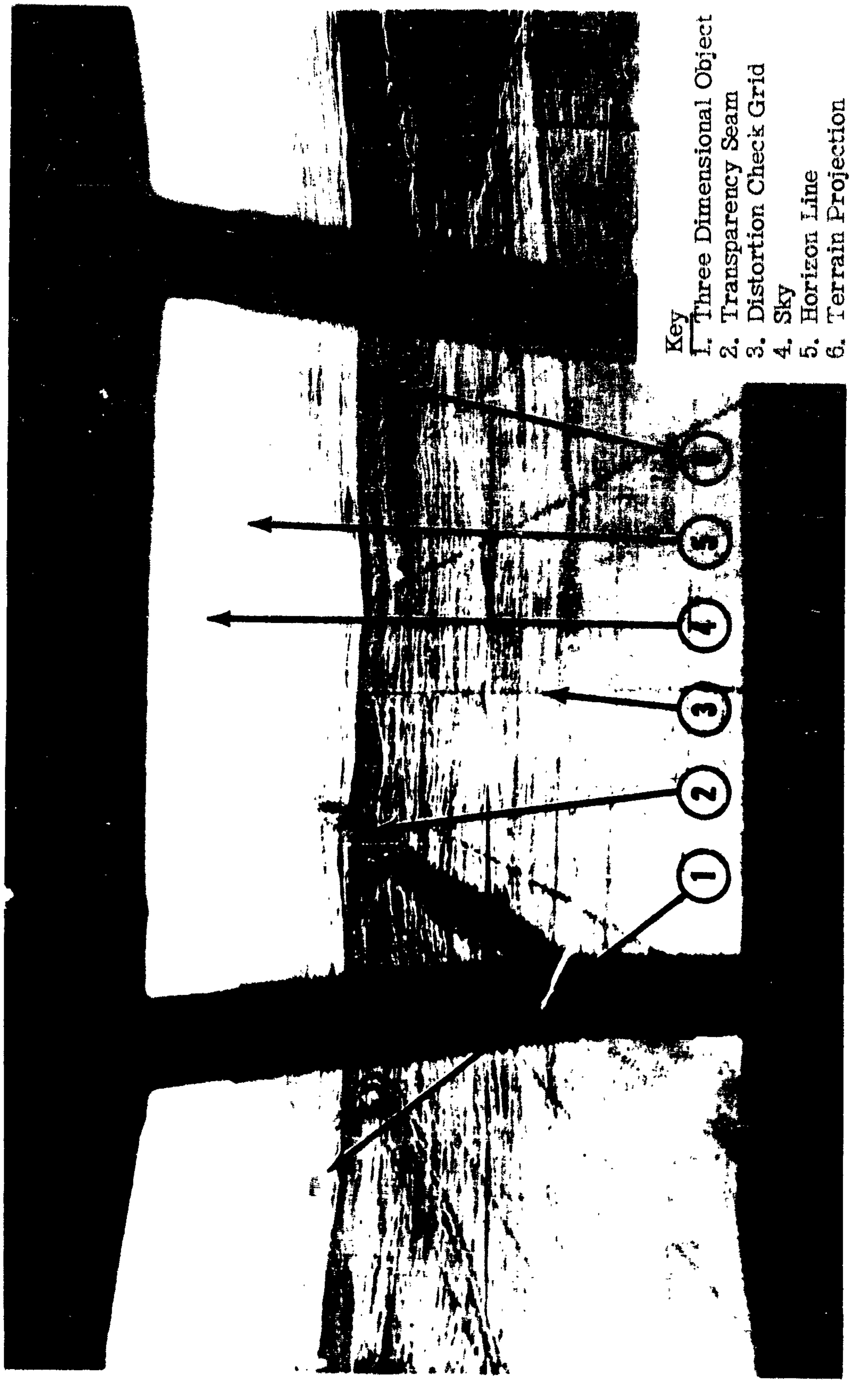
1.1.1 This report describes the results of a study of the components of the point light source projection system made by The de Florez Company, Inc., under contract Nonr 1628(00), for the U. S. Naval Training Device Center. In order to broaden the range of applicability of the point source system as a solution to training problems requiring visual displays, a thorough study of existing components and investigation and development of promising new components was undertaken to increase the versatility of the system. The components studied are the basic ones involved: the point source of light, the display-object and the screen.

1.1.2 When the study began, the size and brightness characteristics of the point light source represented a major limitation to the system. As a result of this study, the qualities of the point light source have been advanced so extensively, that subject matter detail and manufacture of the display-object have become major limitations to the system.

1.2 The Point Source Projection System

1.2.1 The point source projection system produces a continual, moving, wide angle visual display (frontispiece, figures 1-1, 1-2) to an observer who is actually stationary in space. This display is presented with appropriate perspective, size and position relative to the observer, thus simulating the visual world as viewed from any desired position and viewing angle in space. By appropriate movement of the display, the viewing position and angle are changed simulating a corresponding movement of the observer in space. This change in viewing position and viewing angle is smooth and continuous just as it is for an observer actually moving in the real world. In addition, as the observer actually turns his head from side to side or up and down, the wide coverage of the visual display will present a continuous world to either side as well as above and below him.

1.2.2 The simulated movement of the observer on and above the world of the display is completely non-programmed in direction and



Key
1. Three Dimensional Object
2. Transparency Seam
3. Distortion Check Grid
4. Sky
5. Horizon Line
6. Terrain Projection

Figure 1-1 Observer's View of Display-Image (Device 2-FH-5 - View of Visual Mock-Up from Inside Cockpit)

Key
1. Horizon Projector
2. Terrain Projector
3. Cockpit
4. Projection
5. Screen Seams

Figure 1-2 View of a Projection System (Device 2-FH-5 - Visual Mock-Up Projection - Display-Image Distorted due to Camera Position)

is basically limited in extent only by the "ends of the display world." Thus by appropriately attaching the projection system controls to control devices simulating those on a vehicle, aircraft or ship, the observer by manipulation of these controls will have the visual sensation of operating actual controls of the vehicle, aircraft or ship. The world of the visual display will react to each control manipulation by the observer in the same fashion as the actual visual world would react to the corresponding control manipulation by a vehicle operator. The point source projection system then presents a means for the training, practice and testing of control manipulative skills wherever a visual display is mandatory or desirable in the development of such skills. Of course where visual cues together with other sensory cues are necessary, the point source projection system can be combined with other sensation presenting devices to provide a full range of cues to the senses.

1.3 Basic Components

1.3.1 The point source projection system utilizes a very small intense light source to project a display-object onto a screen with appropriate drives and controls to move the light source and display-object relative to one another and with an appropriate supporting structure. The supporting structure and the drives and controls present general engineering problems and are not unique to the point source system. They have therefore been included in this study only to the extent of highlighting special requirements and limitations imposed on them by the point source system. The study has been directed rather to the three basic components of the system: the point source of light, the display-object and the screen and to the inter-relationships of these components as they affect the net end product of the system, the visual display-image as seen by the observer.

1.3.2 The effects of each system variable on display-image quality are reviewed in Chapter 2. These variables include source size and intensity; the display-object line width; the transparency (or reflectivity) and shape of the display-object; screen shape and reflectivity; the properties of light and the position variables: source to display-object distance, display-object to screen distance and the position of the observer relative to the projector components.

1.3.3 Each of the next three chapters, Chapters 3, 4, and 5, is devoted to one of the basic components. Characteristics of components available at the beginning of the study are evaluated in relation to system requirements. New or improved components developed in the

course of the study are evaluated in relation to requirements and expected improvements.

1.4 History

1.4.1 During World War II the point source was applied as a solution to few problems. In particular, it was used to produce shadowgraph projections of solid objects, especially of aircraft models in teaching aircraft recognition.

1.4.2 It wasn't until much later that point source projection was more fully exploited to the extent that elaborate display-objects were substituted for simple objects. A few of the more important recent events in the application of point source follow:

May 1952 - A contract was awarded to Bell Aircraft by the U. S. Navy Special Devices Center to produce a Helicopter Hovering Trainer for the HTL-1 helicopter. Bell assigned the de Florez Company a subcontract to do most of the engineering development on this program.

August 1952 - The feasibility of Point Source Projection, as it is currently used, was demonstrated by the de Florez Co.

February 1953 - de Florez demonstrated a complete mock up including screen, 3' square transparency with 3-D objects, and manually operated projector with six degrees of freedom.

May 1955 - Device 2-FH-2, the first Helicopter Hovering Trainer with a visual attachment was "flown" at Bell Aircraft, Buffalo, N.Y., for the first time.

April 1955 - Device 2-FH-4 Prime Contract was awarded to de Florez by Special Devices Center to develop basic components furthur and investigate possible applications to specific training problems. Under this program the following items were accomplished:

- First Hafnium lamp made having four times the brightness of existing Zirconium lamp with a given source diameter.

- First light source made utilizing meniscus lens to directly reduce an Osram lamp source diameter.

- Application of point source system to training in ground controlled approach (GCA) landings demonstrated.

- Application to training in air-to-air gunnery demonstrated.

- Investigation of all available components.

August 1956 - Device 2-FH-5 Prime contract was awarded to Melpar to develop first complete Helicopter Simulator with visual attachment. Melpar awarded subcontract to de Florez to develop and produce basic components: light source, transparency, and screen.

- Model 1 point source completed utilizing optical system for reduction of real source diameter.

- First photographic flexible transparency completed.

December 1957 - Mock up of 2-FH-5 program was completed utilizing flexible transparency.

1.5 Advantages of the Point Source Projection Technique

1.5.1 The point source projection technique can be used to advantage in training problems requiring visual displays because of its desirable features:

(a.) Presentation of the visual display is non-programmed. The trainee is free to maneuver at will within the range of the trainer.

(b.) The visual display covers a very wide angle, well above the peripheral vision of the human eye. "Off-the-shelf" projection lamps provide displays up to 160 degrees in azimuth while more sophisticated point source projectors can provide displays up to 200 degrees in azimuth. Full 360 degree displays are possible.

(c.) The visual display is sufficiently correct in perspective to be convincing, regardless of the relative viewing position of the observer.

(d.) The display can be presented in color which adds to realism and provides secondary cues to object identification.

(e.) The components utilized in the point source technique are inexpensive particularly when compared with other visual display techniques.

(f.) When necessary, three dimensional objects can be presented in the display in proper perspective contributing greatly to the realism of the illusion.

1.6 Limitations of the Point Source Projection Technique

1.6.1 The point source projection system is subject to some limitations:

(a.) The maximum distance visible in any direction is limited due to the total reflection of light which occurs when rays are incident at acute angles on a transparent medium denser than air. With flat transparent display-objects of commonly available materials the observer's simulated visibility is limited to a distance equal to approximately ten times his simulated viewing altitude.

(b.) Clarity of the display-image varies inversely with simulated altitude. This means that as the observer approaches the ground, the display-image definition deteriorates, a reversal of conditions experienced in real life.

(c.) Perspective is distorted moderately because of the displacement between the observer's eye and the projection source. Distortion of position, and its derivatives, size, velocity and acceleration result.

(d.) Because of limitations on scale resulting from diffraction effects and extended source effects, large

display-objects are required to present extensive training areas. Large display-objects are difficult to produce and require elaborate structures and mechanisms for handling.

CHAPTER 2

The Principles of Point Light Source Projection Techniques

2.1 The Point Source Projection Principle

2.1.1 The principle underlying the point source projection system is analogous to one of the principles by which the eye sees. The eye utilizes the angle subtended by a detail to judge its size, distance and orientation, comparing this angle with angles subtended by details of known size, distance and orientation which are adjacent in the field of view. Thus, in Figure 2-1, the eye cannot distinguish details a1, a2, a3, and a4 from one another if viewed in space without familiar details for comparison. Under the same circumstances it can readily distinguish details b1, b2, b3, and b4 from one another though it cannot determine the factor involved (distance, size, orientation) without binocular convergence, a property of the two eyes used together. Therefore, if the display-image produces the proper angles subtended at the eye of the observer so that relative size, orientation, and distance of details in the field of vision are in the regularly seen relation to one another, the display-image will be registered by the eye as identical to the same set of details in the real world.

2.1.2 Figure 2-2 shows that, if the angle subtended at the point source by the display-object is varied by adjusting orientation, distance and size of the display-object relative to the point source, the display-image change is analogous to the changes in Figure 2-1b, provided that the eye is held at the same point as the point source or at the corresponding position on the opposite side of the screen. It can be said that if the eye is concurrent with the real image of the point source (same side of screen) or with the virtual image of the point source (opposite side of screen) relative to the screen as an image-forming surface, the observer will have the same point of view to the display-image as the point source has to the display-object and the display-image will be true to the display-object in relative size of details, in distance between details and in perspective.

2.2 Arrangement of Components

2.2.1 For distortion free projection, the point source components must be arranged as shown in Figures 2-3a and 2-3b. It is obvious from Figure 2-3a that the eye cannot be placed concurrent with the

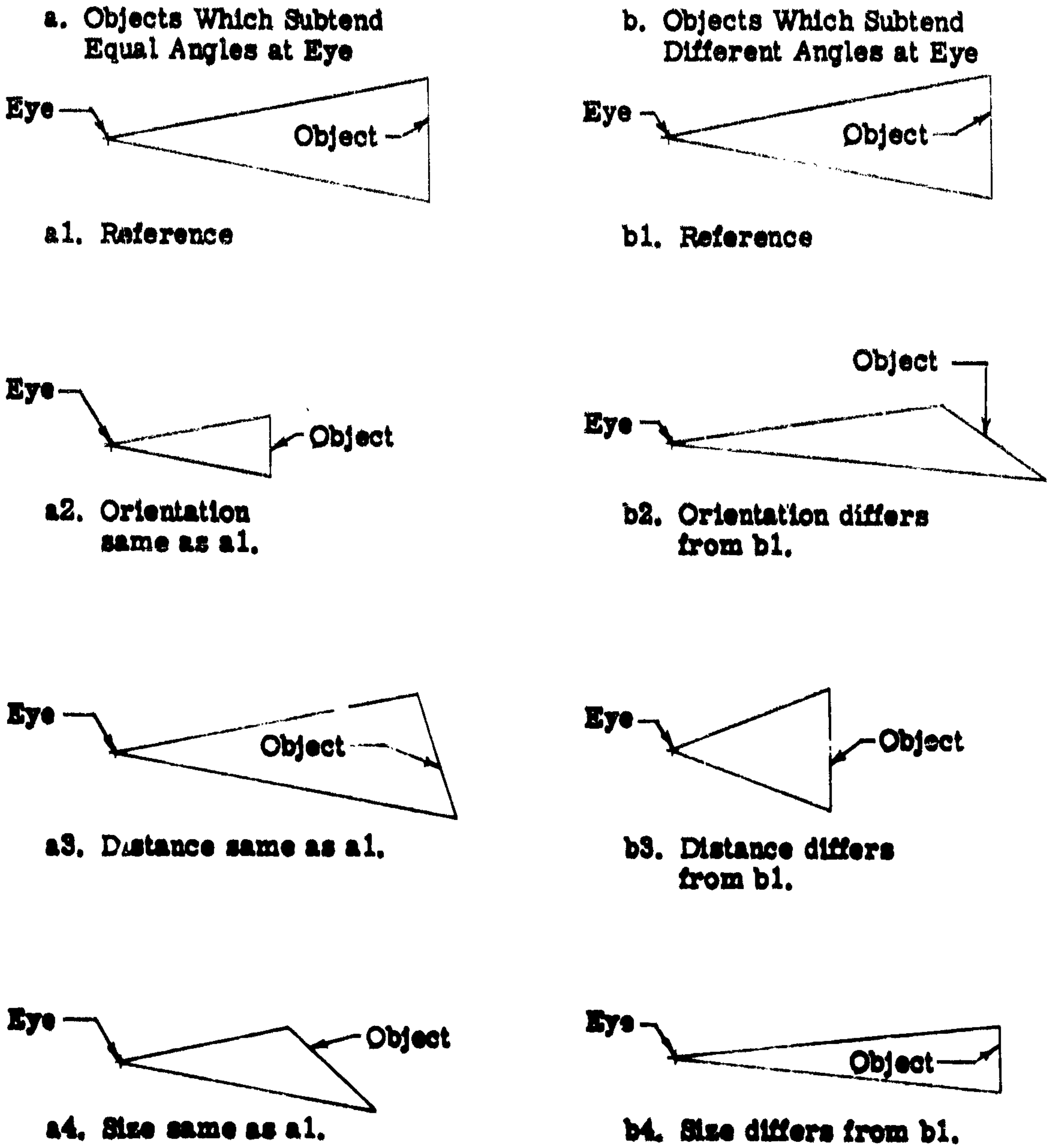


Figure 2-1 **Schematic Showing Effects of Size, Distance and Orientation of Objects in Space on the Angle Subtended at the Eye of an Observer.**

Display Objects Which Subtend Different Angles at the Point Source

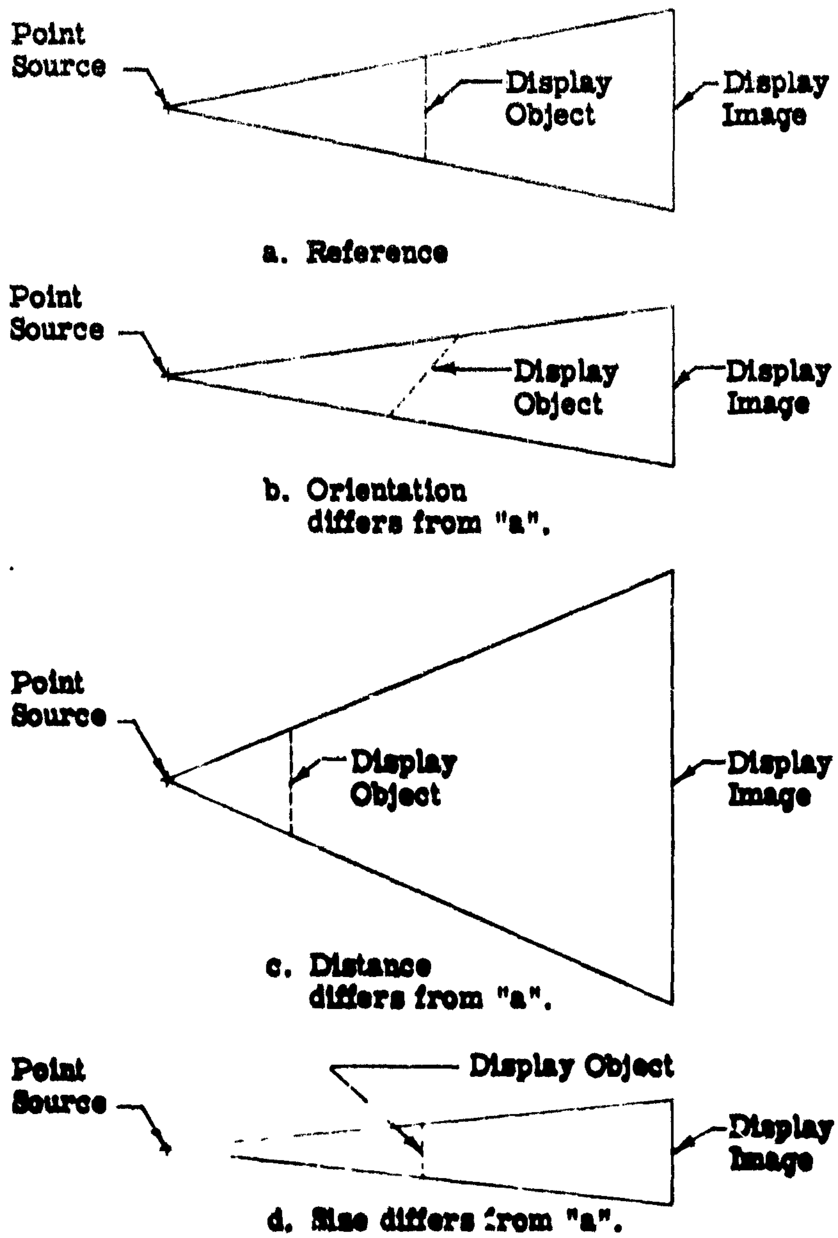
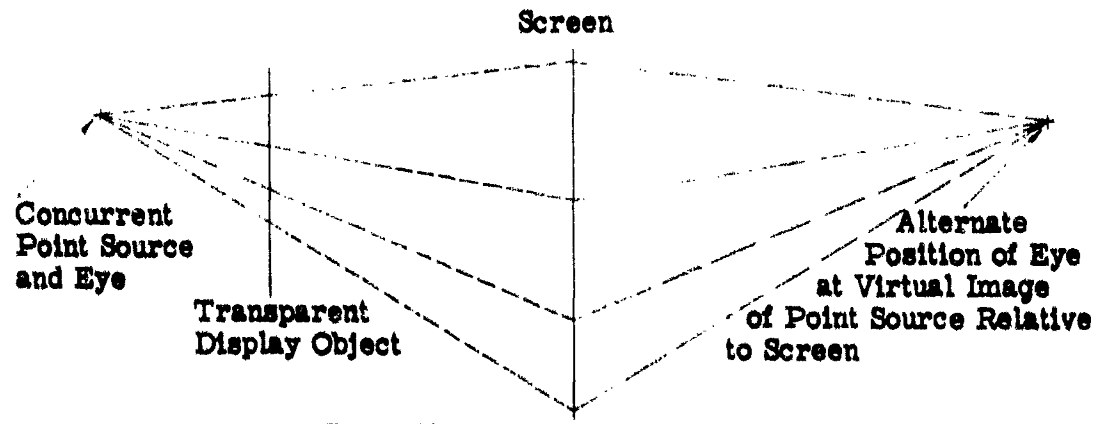
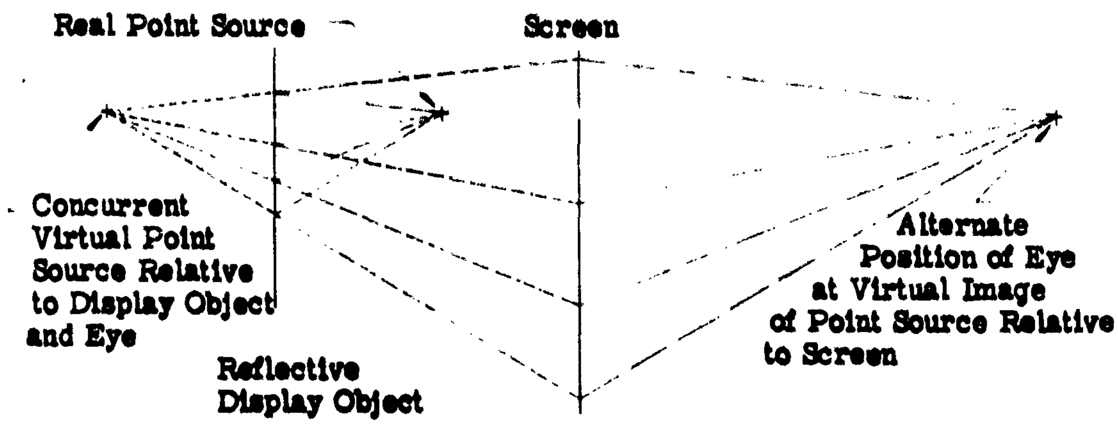


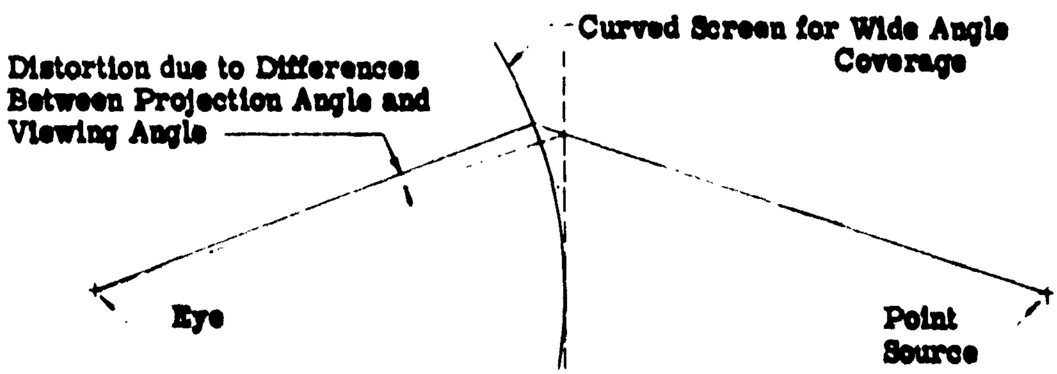
Figure 2-2 Schematic Showing Effects of Display Object Size, Orientation and Distance Relative to a Point Source on Display Image and on Angle Subtended at the Point Source.



a. Projection of Transparent Display Object



b. Projection of Reflective Display Object



c. Rear Screen Projection on Curved Screen

Figure 2-3 Schematics of Component Arrangements of Point Source Projection Systems.

point source, first, because both cannot occupy the same space and, second, because the eye would then see the display-object and not the display-image. In figure 2-3b the eye cannot be placed concurrent with the virtual image of the point source relative to the display-object because the reflective type display-object would conceal the screen. Location of the eye at the alternate position, the virtual image point of the point source relative to the screen is free from distortion only when a flat screen is used. However, a flat screen provides only a limited angle of coverage. The angle of coverage can be increased by curving the screen around the observer, but the viewing angle is distorted as shown in figure 2-3c because the projection distance increases while the viewing distance remains constant.

2.2.2 The point source and display-object form an obstruction to the observer's view which in most instances is best located in the blind area above his head or behind him. At the same time the observer's head and body form an obstruction to projection which is best located in one of the observer's blind areas, in most cases, directly below him. To achieve these conditions the point source is located directly above the observer and the display-object is also above him. Schematic diagrams of some practicable arrangements of components are shown in figure 2-4.

2.3 Determination of Scale Ratios

2.3.1 The ratio of the size of details on the display-object to the size of these details in the real world is the scale or scale ratio of the projection system. The scale ratio must be the same in all three axes in space; i.e., if the scale ratio of length is 2:1. the scale ratio of width and height must also be 2:1. The determination of this ratio is of great importance for its numerical value determines the size of display-object needed to provide the extent of real world desired. The size of the display-object so determined will, in turn, dictate the size and type of mechanical equipment needed to move it. Figure 2-5 illustrates how the display-object scale ratio is determined. All terms must be expressed in the same dimensional terms. The screen distance and theoretical magnification are not considered in determining scale ratios, for by placing the observer's eye as close as possible to the point source the observer's viewing angle is essentially the same as the point source projection angle and the subtended angles are essentially equal and true to size. These errors are discussed in detail in paragraph 2.4.

2.3.2 The effects of an extended source and of diffraction on display-image definition, discussed in paragraphs 2.6.3 and 2.7, are major

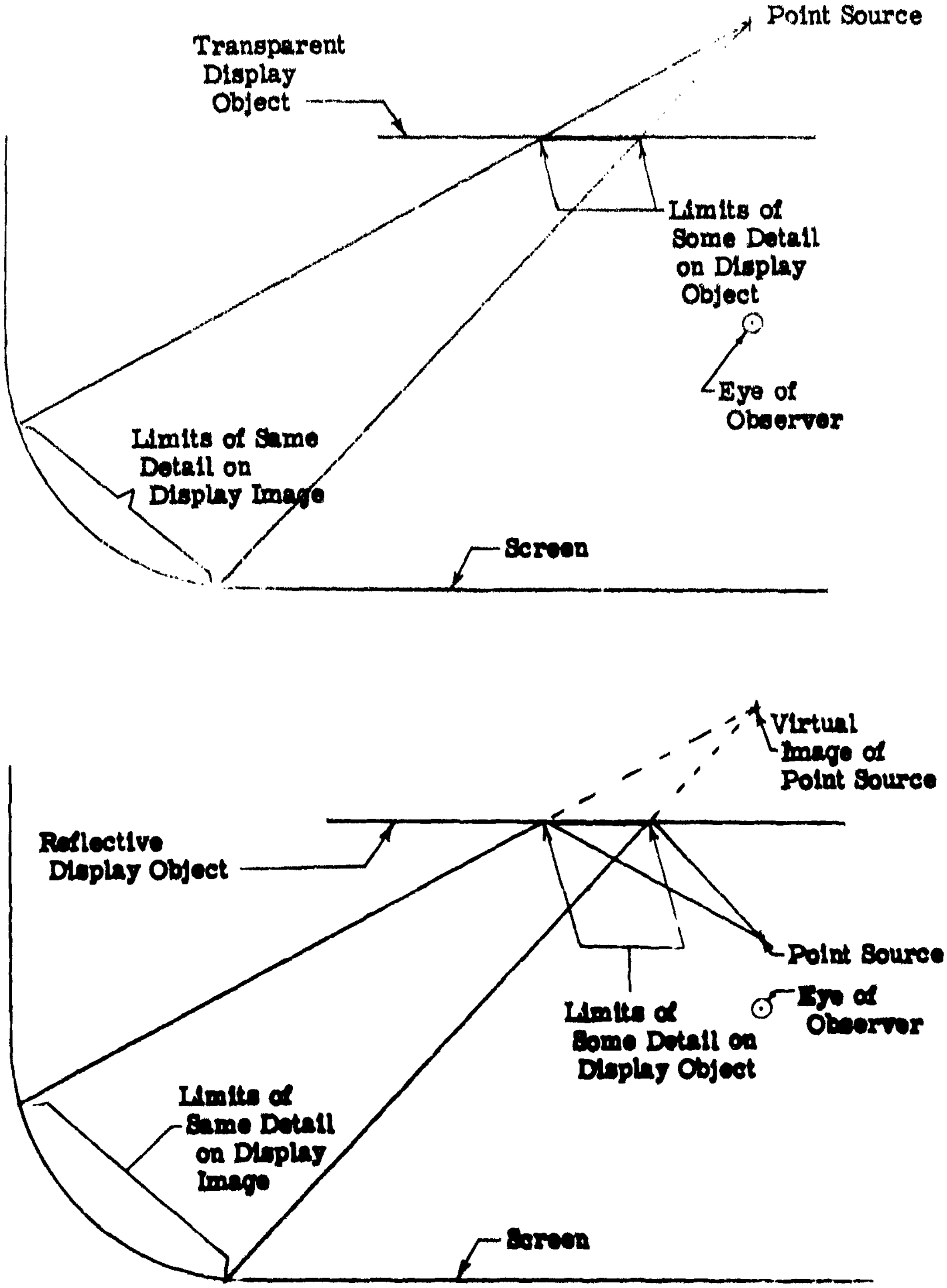
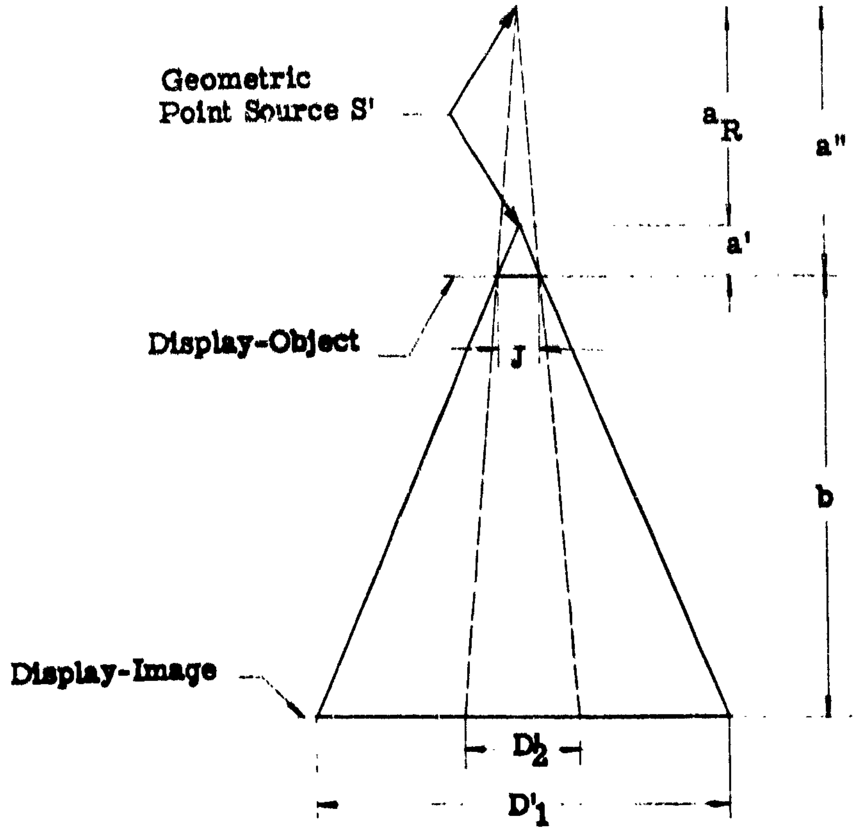


Figure 2-4 - Schematic Diagrams of Point Source Projection Systems Using Transparent and Reflective Display-Objects.



By definition P = A/a and M = D'/J.

From these, in the diagram

$$P = A'/a' = A''/a'' = A_R/a_R$$

$$A_R = A'' - A' = P(a'' - a')$$

$$M' = D'_1/J = (a' + b)/a'$$

$$M'' = D'_2/J = (a'' + b)/a''$$

Note that while the diagram shown is for a transparent display-object, the same relationships are developed for a reflective display-object.

Figure 2-5 - Determination of Scale Ratio P and of Theoretical Magnification M from Conditions to be Simulated.

factors in determining scale ratio. These effects and the point source envelope dimensions limit the minimum distance between the point source and the display-object. In turn, this minimum distance must represent at least the minimum altitude to be simulated. The limitation imposed by the point source envelope, being physical, is absolute while the limitation imposed by extended source effects and diffraction effects affect display-image quality and can be adjusted to the extent that display-image quality at the lower end of the simulated altitude range can be compromised. The maximum distance permissible between the point source and the display-object is limited by the extent to which the distortion of the display-image, caused by the corresponding increase in the point source to eye displacement, can be tolerated. Because of the retro-directive nature of beaded screens, as discussed in Chapter 5, large distances between the point source and the eye result in decreases in display-image brightness which can be serious. A third limitation on scale ratio determination is the economic and technical problem of producing display-objects with very large scale ratios as discussed in Chapter 4.

2.3.3 These limitations indicate that display-object scale ratios must often be determined through compromises. Determined solely on the basis of picture definition, the display-object scale ratio may be too low for a display-object of desired area coverage so that the display-object becomes too large and unwieldy. This may create a need for a very large and complex mechanical system for moving the display-object which in turn will impose a severe handicap on the design and complexity of the servo drives.

2.3.4 Very high scale ratios present their own difficulties. Display-objects of very large ratios are difficult, sometimes impossible to prepare. In addition, servo jitter must be eliminated since velocity errors and oscillations are considerably magnified.

2.4 Distortions Due to Displacement Between the Eye and the Point Source

2.4.1 Displacement between the observer's eye and the point source leads to several types of display-image distortions which result in an erroneous visual presentation with regard to scene perspective, and, when the scene moves relative to the observer, with regard to apparent velocity and acceleration of an object. If these distortions are excessive the realism of the visual display may be so far impaired as to destroy its value as a training device. Although it is not possible

to completely eliminate these distortions, it is possible to reduce them to a minimum by proper selection of system geometry and screen shape. These distortions may be grouped in three classifications: position distortion, size distortion, and velocity distortion. Size and velocity distortions are derived from position distortion.

2.4.2 For purposes of this discussion, the point source, the eye, and the display-image are considered in the same vertical plane. Since the screen is assumed to be symetrical about the point source in the horizontal plane, the viewing angle and the projection angle will be identical and no distortion will be introduced in this plane. Some additional distortion is introduced when the eye is outside of the vertical point source - image plane, but this can be made insignificant by keeping the eye to plane distance small.

2.4.3 Position Distortion

2.4.4 Position distortion may be defined as the difference between the angle of projection to a point on the display-image and the viewing angle from the eye to the same point on the display-image. (Appendix I, figures I-1, I-2 and I-3) Position distortion depends upon the point source to eye distance, the point source to screen distance, the geometric relationship of the eye to the point source and the screen, the angle of viewing, and the shape of the screen. Expressions for position distortion in terms of these variables have been derived in Appendix I and are the basis for the following illustrations and discussion. Throughout this discussion, the viewing angle is positive below the horizontal and negative above.

2.4.5 Recalling that a convenient geometric arrangement is one where the point source is located directly above the eye, the position distortion, η , is plotted in figure 2-6 as a function of viewing angle, δ , for three fundamental screen shapes: a flat vertical screen, a flat horizontal screen, and a circular screen centered at the point source. Three values of the ratio of point source to eye distance to point source to screen distance, v/d, (0.05, 0.20, 0.35) were selected because in the usual point source projection system the point source to eye distance is expected to vary from 1 to 3 feet and the point source to screen distance is expected to vary from 8 to 20 feet.

2.4.6 The meaning of these curves in terms of an observer's view of the display-image may best be illustrated with an example. If the observer's eye is located 3' directly below the point source and a vertical screen is located 15' from the point source (v/d = .20), a point projected on the screen so that it is observed at a viewing angle 50^o below the horizontal ($\delta = 50^o$) would be seen 54^o below the horizontal if viewed from the point source ($\eta = 4^o$). Similarly at ground level an observer would expect to see the horizon directly in front of him at or slightly

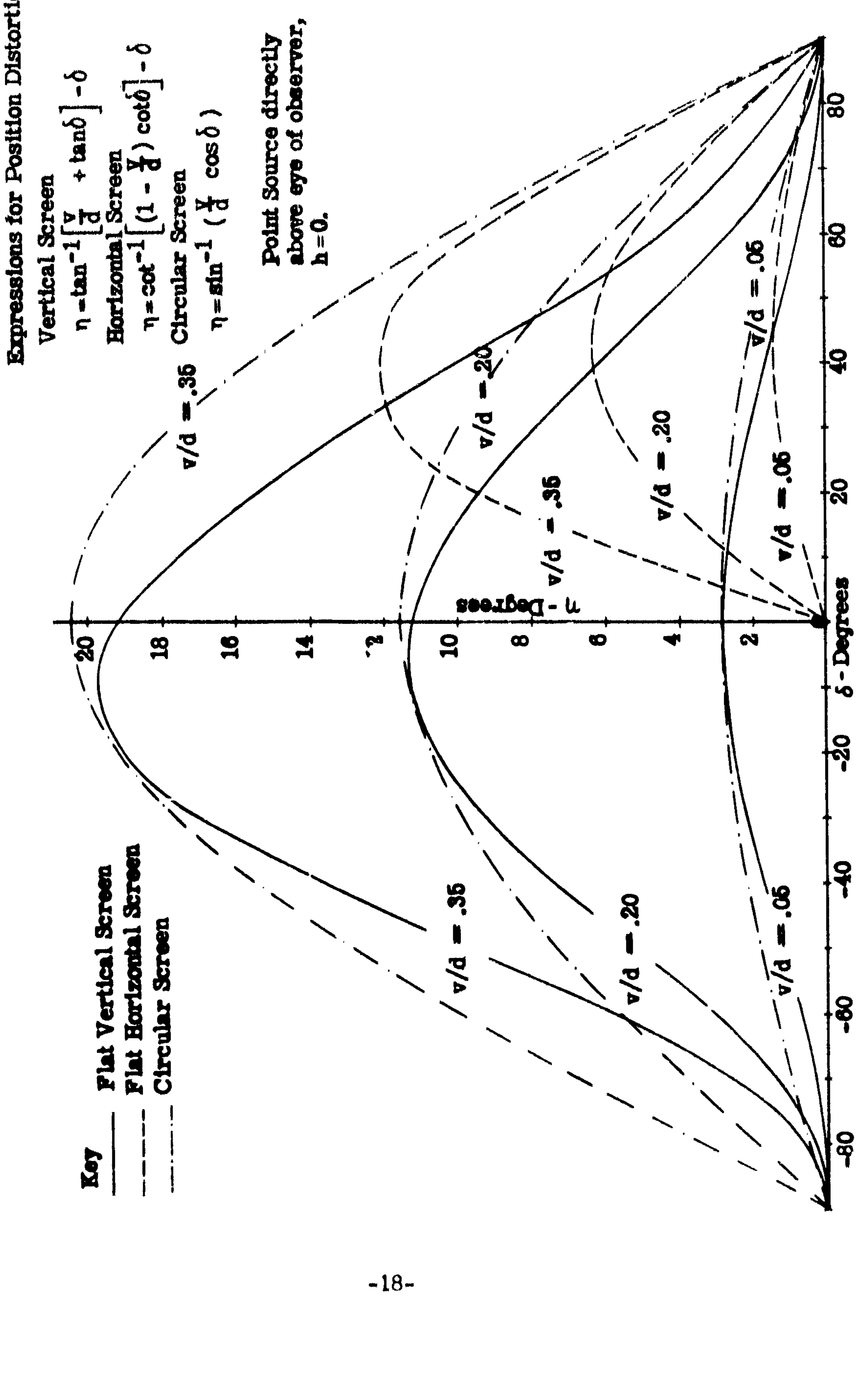
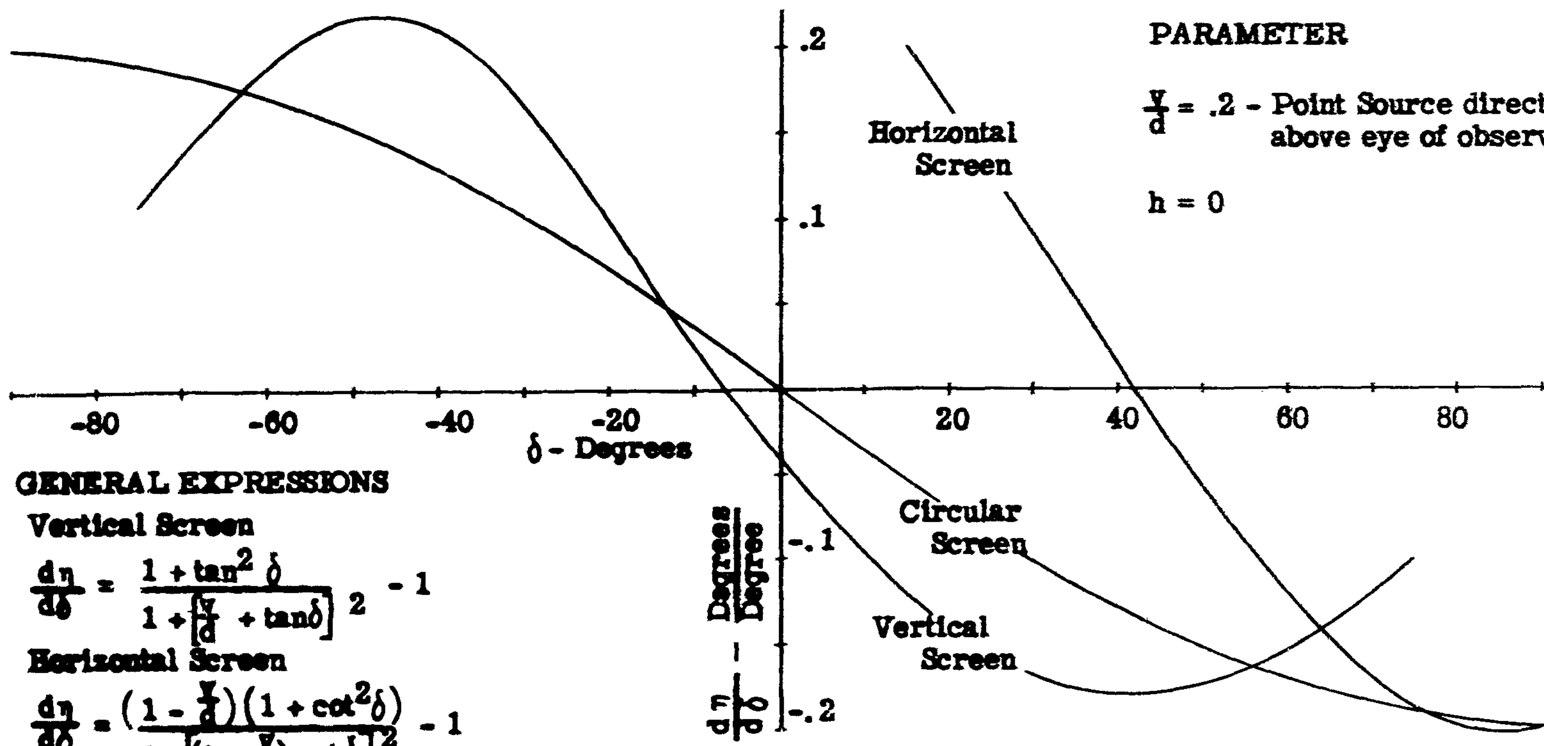


Figure 2 - 6 - Position Distortion, η, on Basic Screen Shapes at Viewing Angle, δ, for Selected System Parameters.

below his eye level ($\delta \gtreqless 0^{o}$) whereas it will be projected on the screen so that he sees this horizon point 11.5^{o} above his eye level ($\eta = 11.5^{o}$). As a result of position distortion the observer sees each projected point higher than he should and he will consider each point to be more distant than it actually is. The over-all effect of this distortion in terms of a particular terrain display is the so-called "bowl effect"; that is the observer sees the entire horizon line somewhat higher than normal and he feels that the contour of the terrain is bowl shaped and that he is located at the low point in the bowl. Another position distortion phenomenon which seems to contribute to "bowl effect" is the slight curvature in the observer's view of the display-image of any straight line on the display-object introduced by curvature of the screen. The phenomenon is quite readily explained by considering that the point source and a straight line on the display-object form a plane which intersects the screen surface to form the display-image of the line. From consideration of solid geometry it can be seen that the intersection of this point source - display-object-line plane with a flat screen (another plane) is a straight line in space regardless of viewing position but that the intersection of this plane with any curved screen is a curved line in space and will appear curved from any viewing position in space which is not in the point source - display-object-line plane. In normal point source systems where the observer is below the point source and the screen is partly cylindrical and partly torus shaped, almost all projected straight lines appear to the observer to curve upward at the ends. The curvature is caused directly by displacement of the observer from the projection source and by screen curvature.

2.4.7 From the curves in figure 2-6 it is evident that the smaller the value of the ratio, v/d, the smaller the position distortion at all viewing angles and for all screen shapes considered. Furthermore, the horizontal screen shows lower distortion than either of the other shapes. At v/d equal to 0.20, maximum distortion on the horizontal screen is 6^{o} 23' and occurs at a viewing angle of 41^{o} 48' below the horizontal. The maximum distortion on the vertical screen is 11^{o} 26' at a viewing angle of 5^{o} 43' above the horizontal while maximum distortion on the circular screen is 11^{o} 32' at a horizontal viewing angle. When viewing directly ahead or at small angles above or below the horizontal, position distortion is maximum for vertical and circular screens and minimum for horizontal screens. (Of course the horizontal screen cannot be viewed at an angle above the horizontal.) Position distortion directly above and below the observer is zero. Note that position distortion on the circular screen is greater than on the vertical screen particularly at viewing angles below the horizontal.

2.4.8 It is of interest to note the rate at which position distortion changes as the viewing angle changes over the limits of visibility. Figure 2-7 shows this rate of change, $d\eta/d\delta$, for v/d equal to 0.20. Note that the circular screen provides an almost uniform rate of change of position distortion over the full range of viewing angles. The rate of change of position distortion provided by the horizontal screen is also quite uniform in the area between 15^{o} below the horizontal and 75^{o} below the horizontal. This represents a major



GENERAL EXPRESSIONS

Vertical Screen

$$\frac{d\eta}{d\delta} = \frac{1 + \tan^2 \delta}{1 + \left[\frac{y}{d} + \tan\delta\right]^2} - 1$$

Horizontal Screen

$$\frac{d\eta}{d\delta} = \frac{\left(1 - \frac{y}{d}\right)\left(1 + \cot^2\delta\right)}{1 + \left[\left(1 - \frac{y}{d}\right)\cot\delta\right]^2} - 1$$

Circular Screen

$$\frac{d\eta}{d\delta} = \frac{\frac{y}{d}\sin\delta}{\left[1 - \left(\frac{y}{d}\cos\delta\right)\right]^2}$$

Figure 2-7 - Rate of Change of Position Distortion, dη/dδ, with Viewing Angle, δ, for Three Basic Screen Shapes for Selected System Parameters.

portion of the useful projection area on a horizontal screen. Rate of change of position distortion on the vertical screen is subject to considerable variation.

2.4.9 Figures 2-8, 2-9, and 2-10 illustrate the effect of varying the horizontal distance, h, between the observer's eye and the point source (v positive). In all cases the point source remains above the level of the observer's eye. When h is positive the point source is behind the observer and when h is negative the point source is forward from the observer. When the point source is moved back from the observer distortion at viewing angles below the horizontal is decreased and distortion at viewing angles above the horizontal is increased. The values of distortion that are negative are completely theoretical because the observer's head will interfere with projection and no image will be formed at these viewing angles. When the point source is moved forward from the observer's position, position distortion is increased for viewing angles below the horizontal and is decreased for viewing angles above the horizontal. Here negative distortion values are hypothetical because the point source will interfere with the observer's view of the screen. From these curves it may be concluded that when a display-image directly below the observer or at large angles below the horizontal is not required, position distortion on the remaining portion of the display-image below the horizontal can be reduced by moving the point source back from the observer. Location of the point source forward of the observer should be avoided except where features very close to or beneath the feet of the observer are absolutely essential to the display-image requirements of a problem.

2.4.10 The rate of change in position distortion with change in viewing angle $d\eta / d\delta$, for the conditions where the point source is located forward or behind the observer is shown on figures 2-11, 2-12, and 2-13 for v/d equal to .20. When the point source is moved to a position forward of the observer's eye (h negative) the rate of change of position distortion on both vertical and circular screen becomes more uniform at viewing angles below the horizontal but becomes more irregular at points immediately above the horizontal. When projected on the horizontal screen the rate of change of distortion becomes more irregular at viewing angles just below the horizontal. When the point source is moved to a location behind the observer's eye (h positive) the rate of change of position distortion is more uniform on a vertical screen at viewing angles greater than 40° below the horizontal but is more irregular between the horizontal and a viewing angle 40° below it. On the horizontal screen the rate of change of position distortion becomes more irregular over the entire range of viewing angles. On the circular screen the rate of change of position distortion is also less uniform at viewing angles below the

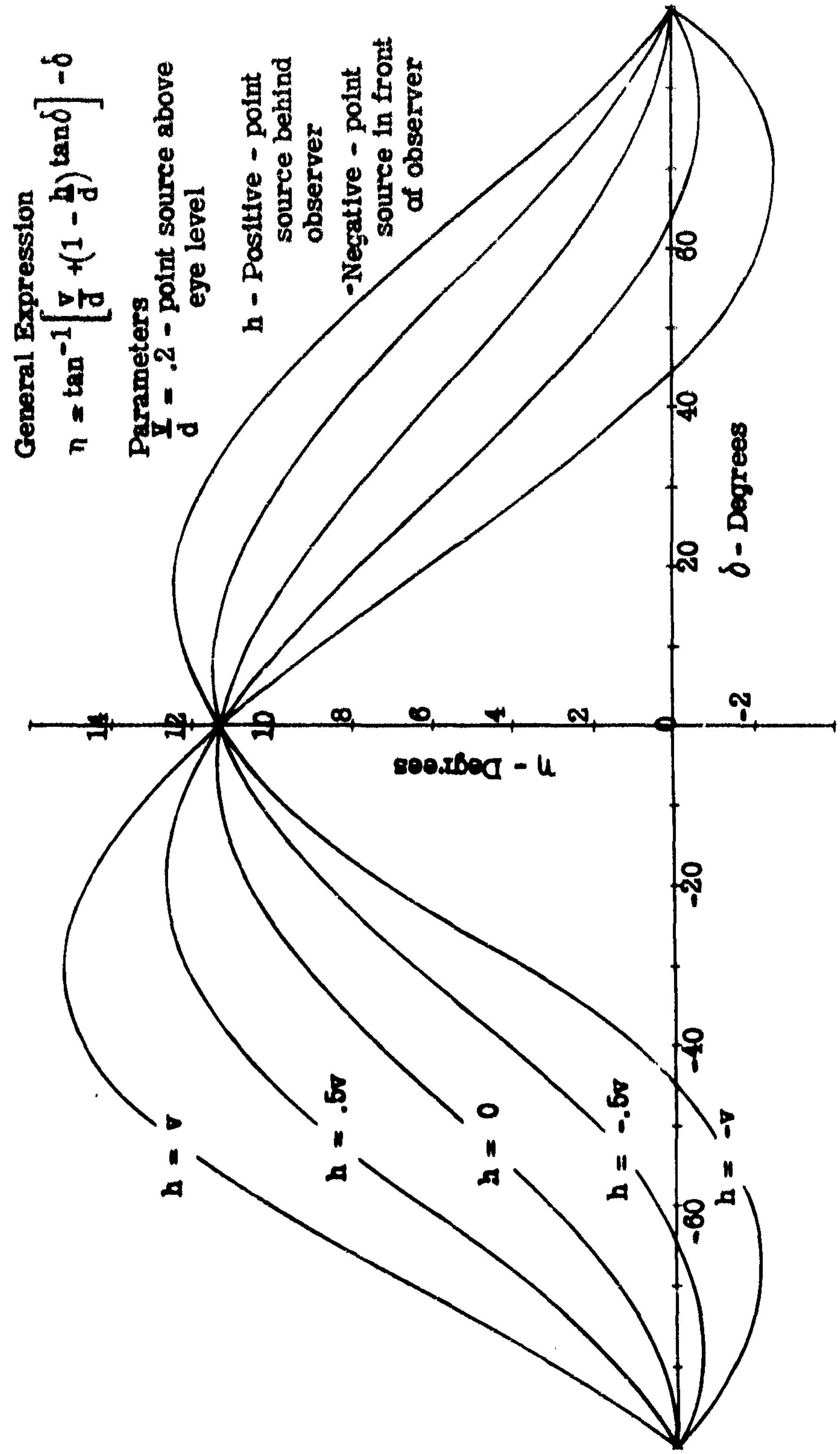


Figure 2-8 - Position Distortion, η, on a Flat Vertical Screen at Viewing Angle, δ, for Selected System Parameters.

General Expression

$$\eta = \cot^{-1}\left[\frac{h}{d} + \left(1 - \frac{v}{d}\right)\cot\delta\right] - \delta$$

Parameters:

v/d = .2 - point source above eye level

h - Positive - point source behind observer

- Negative point source in front of observer

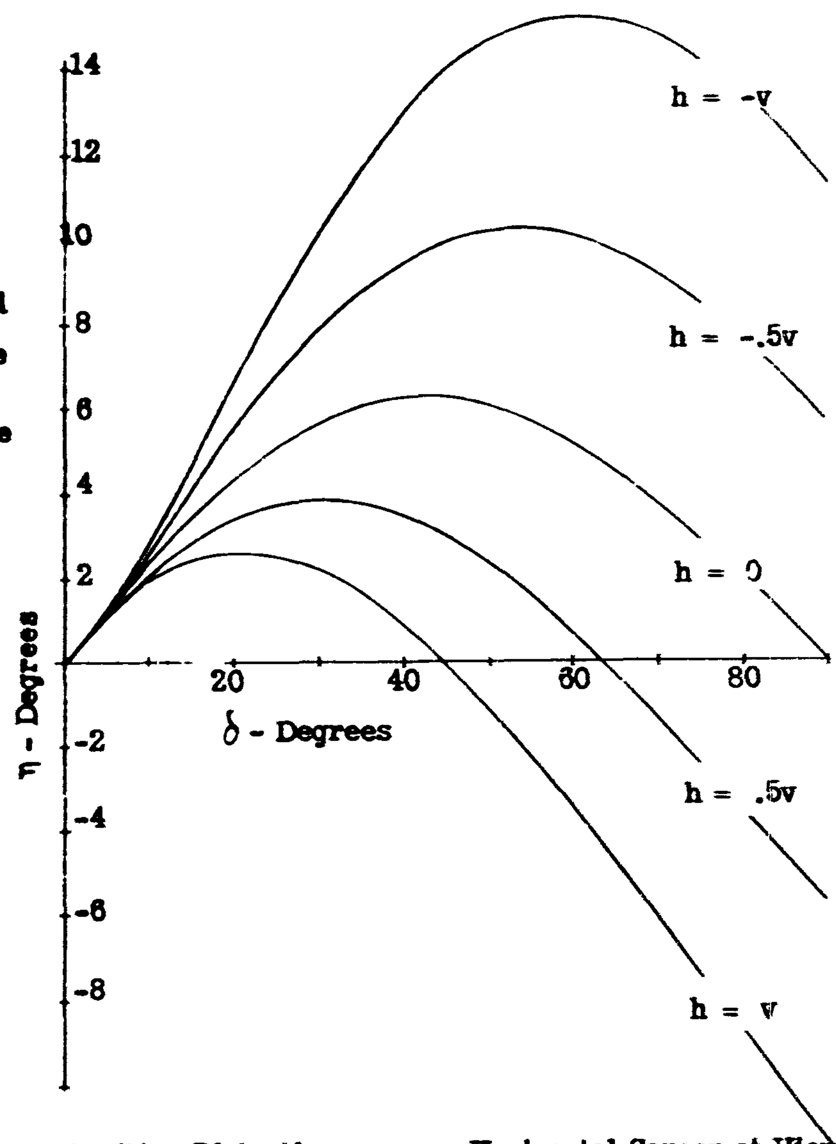


Figure 2-9 - Position Distortion, η, on a Horizontal Screen at Viewing Angle, δ, for Selected System Parameters.

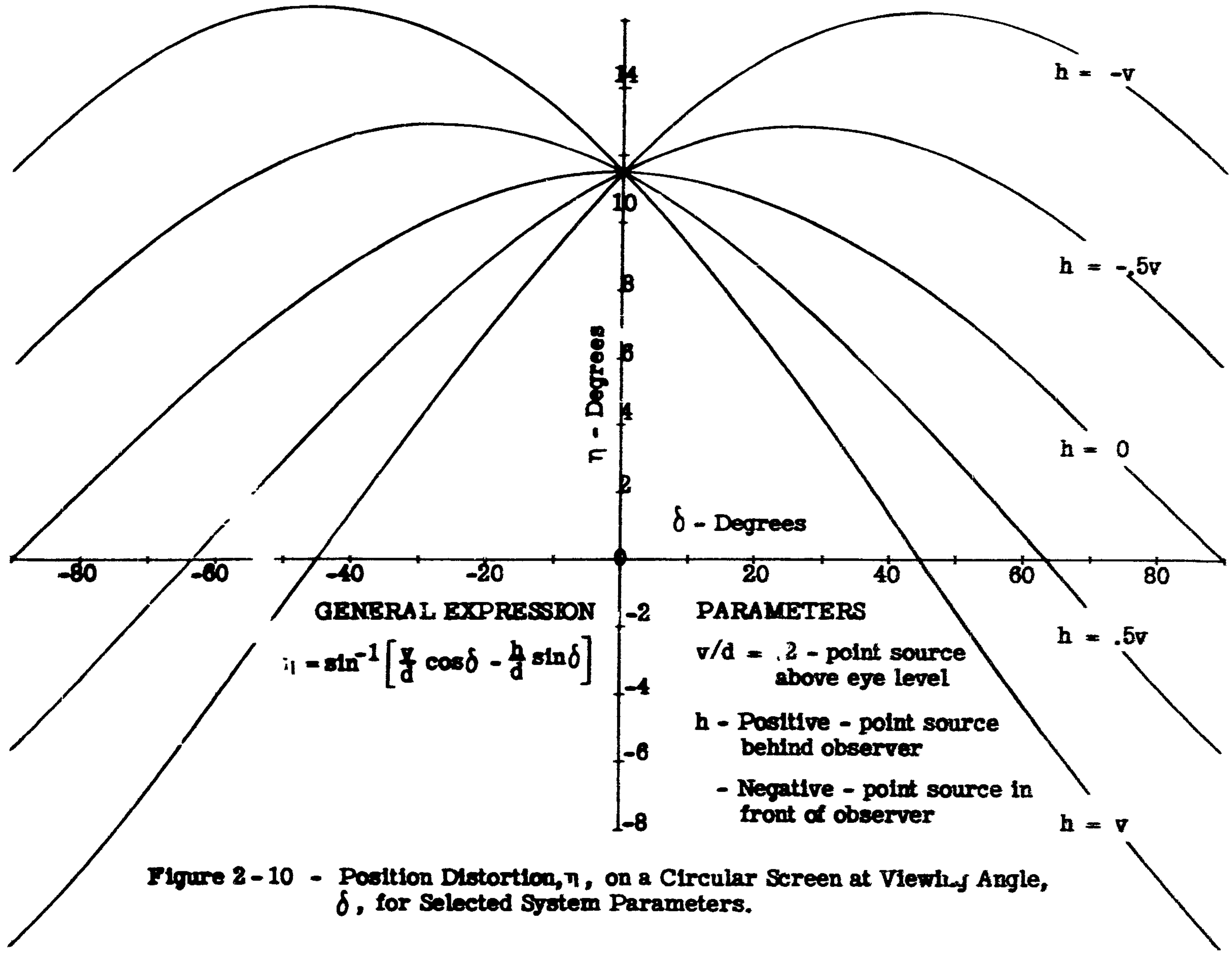


Figure 2-10 - Position Distortion, η, on a Circular Screen at Viewing Angle, δ, for Selected System Parameters.

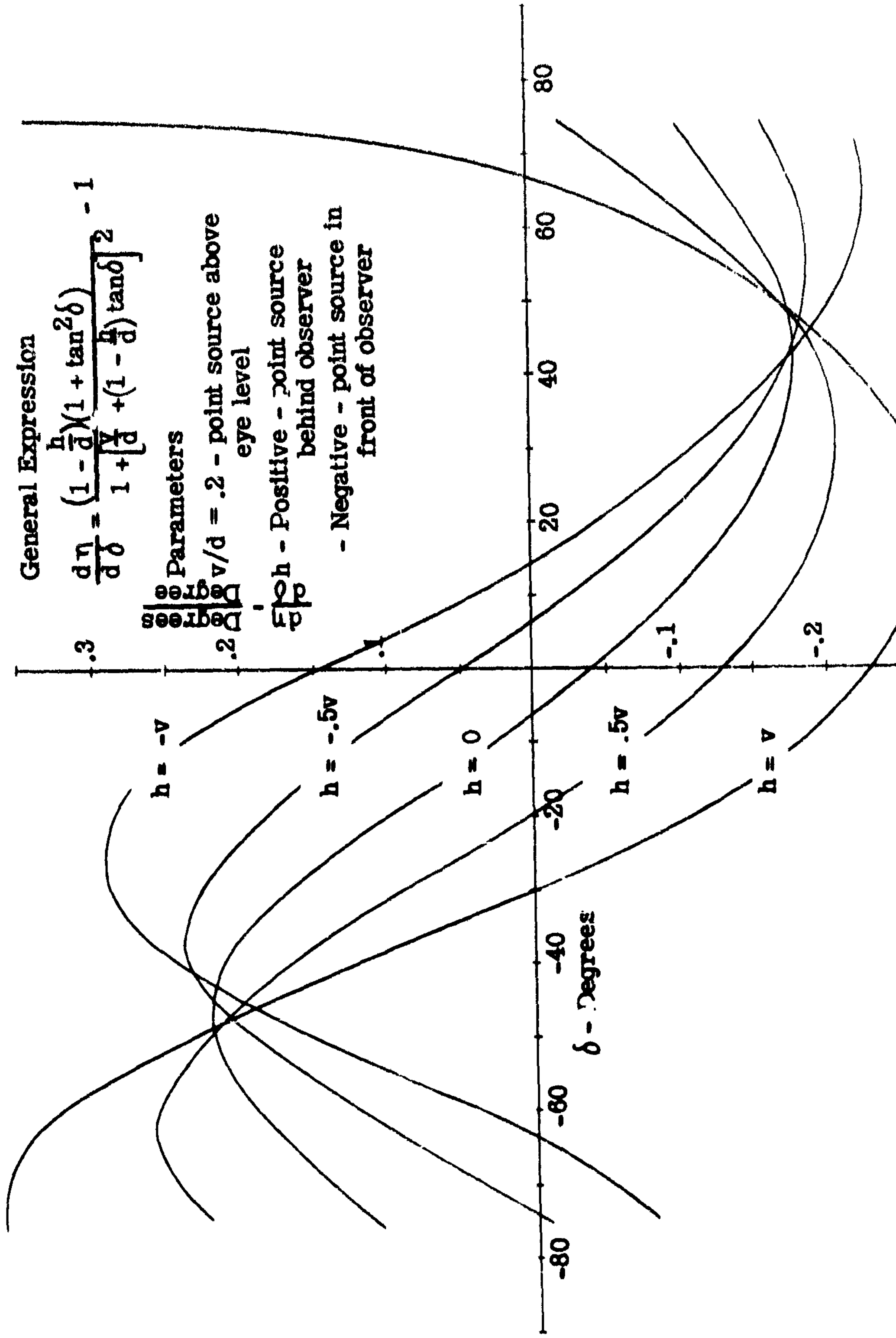


Figure 2-11 - Rate of Change of Position Distortion, $d\eta/d\delta$, on a Flat Vertical Screen at Viewing Angle, δ, for Selected System Parameters

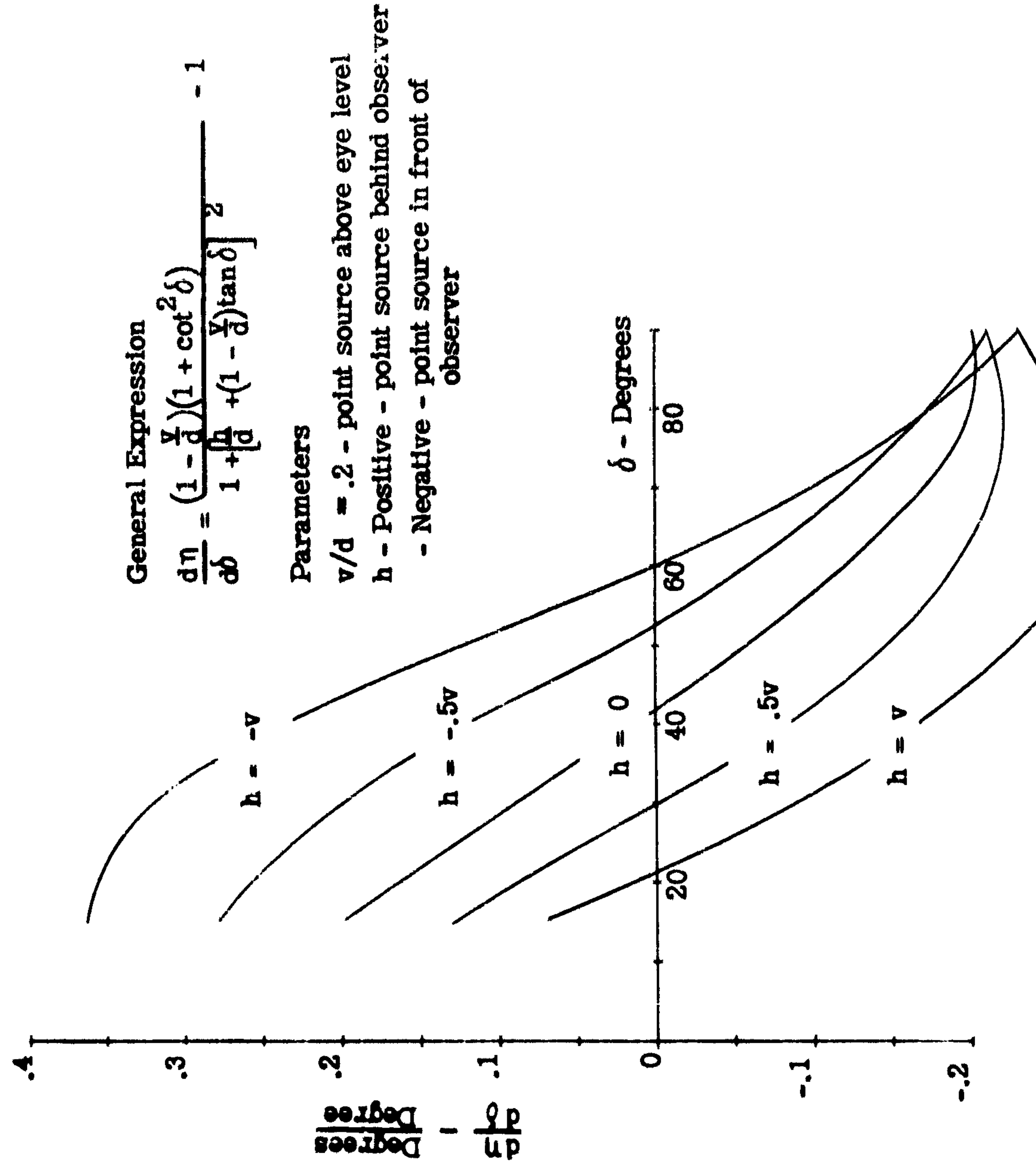
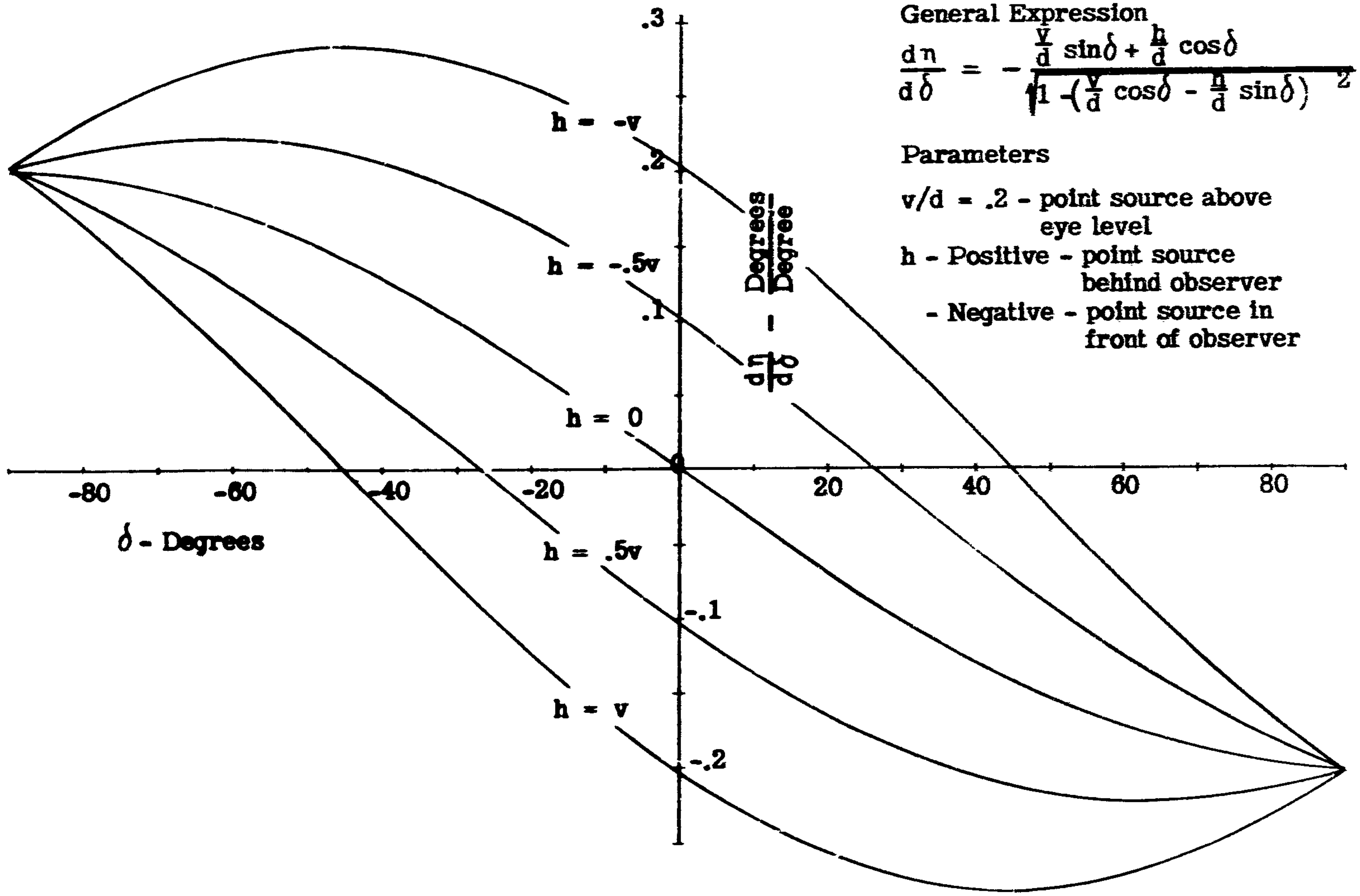


Figure 2-12 - Rate of Change of Position Distortion, $d\eta/d\delta$, on a Horizontal Screen at Viewing Angle, δ, for Selected System Parameters



General Expression

$$\frac{d\eta}{d\delta} = -\frac{\frac{v}{d}\sin\delta + \frac{h}{d}\cos\delta}{\sqrt{1-\left(\frac{v}{d}\cos\delta - \frac{h}{d}\sin\delta\right)^2}}$$

Parameters

v/d = .2 - point source above eye level

h - Positive - point source behind observer

- Negative - point source in front of observer

Figure 2 - 13 - Rate of Change of Position Distortion, $d\eta/d\delta$, on a Circular Screen at Viewing Angle, δ, for Selected System Parameters.

horizontal.

2.4.11 Rate of change of position distortion is analogous to the distortion of the velocity of a point on the display-image when the display-object is moved. The more uniform the rate of velocity distortion the less likely it is that the observer will detect it. Therefore, it can be seen that a uniform rate of change of position distortion is desirable particularly when the display-image requirements include visual cues to velocity.

2.4.12 Size distortion

2.4.13 Position distortion of the end points of an object lead to distortion in its size, so that the object appears smaller or larger than it actually is. Size distortion is dependent upon the same variables as position distortion and in addition is dependent upon the size of the object viewed. Size distortion in combination with position distortion results in a distortion of perspective in the display-image.

2.4.14 The effect of size distortion was studied by considering an object on the display-image subtending an angle, $\Delta\delta = 10^{\circ}$, at the eye of the observer. As this object is viewed at different viewing angles, δ, size distortion, $\Delta\eta$, assumes values as shown in figure 2-14 when v/d is equal to .20 and h is equal to 0. Positive values of size distortion, $\Delta\eta$, mean that the object is actually larger than it appears while negative values mean that the object is smaller. Thus an object viewed at 35° below the horizontal on a vertical screen appears to be 10° in size but is actually only 8.25° ($\Delta\eta = -1.75^{\circ}$). An 8.5° object viewed at an angle 20° below the horizontal and an 11.5° object viewed at an angle 25° above the horizontal on the same vertical screen will both appear to be 10° in size.

2.4.15 The curves of figure 2-15 show the distortion in size, $\Delta\eta$, of a 10° object over the range of viewing angles, δ, as the point source is moved forward (h negative) and back (h positive) relative to the observer. Note that a family of curves can be established for every size object (different values of $\Delta\delta$). One of the effects of size distortion is to lead to false judgements of distances. Thus, an object which appears larger than it actually is seems closer to the observer than it actually is.

2.4.16 The rate of change of the size of an object, $d\Delta\eta/d\delta$, as the viewing angle, δ, is varied provides a cue to the velocity with which

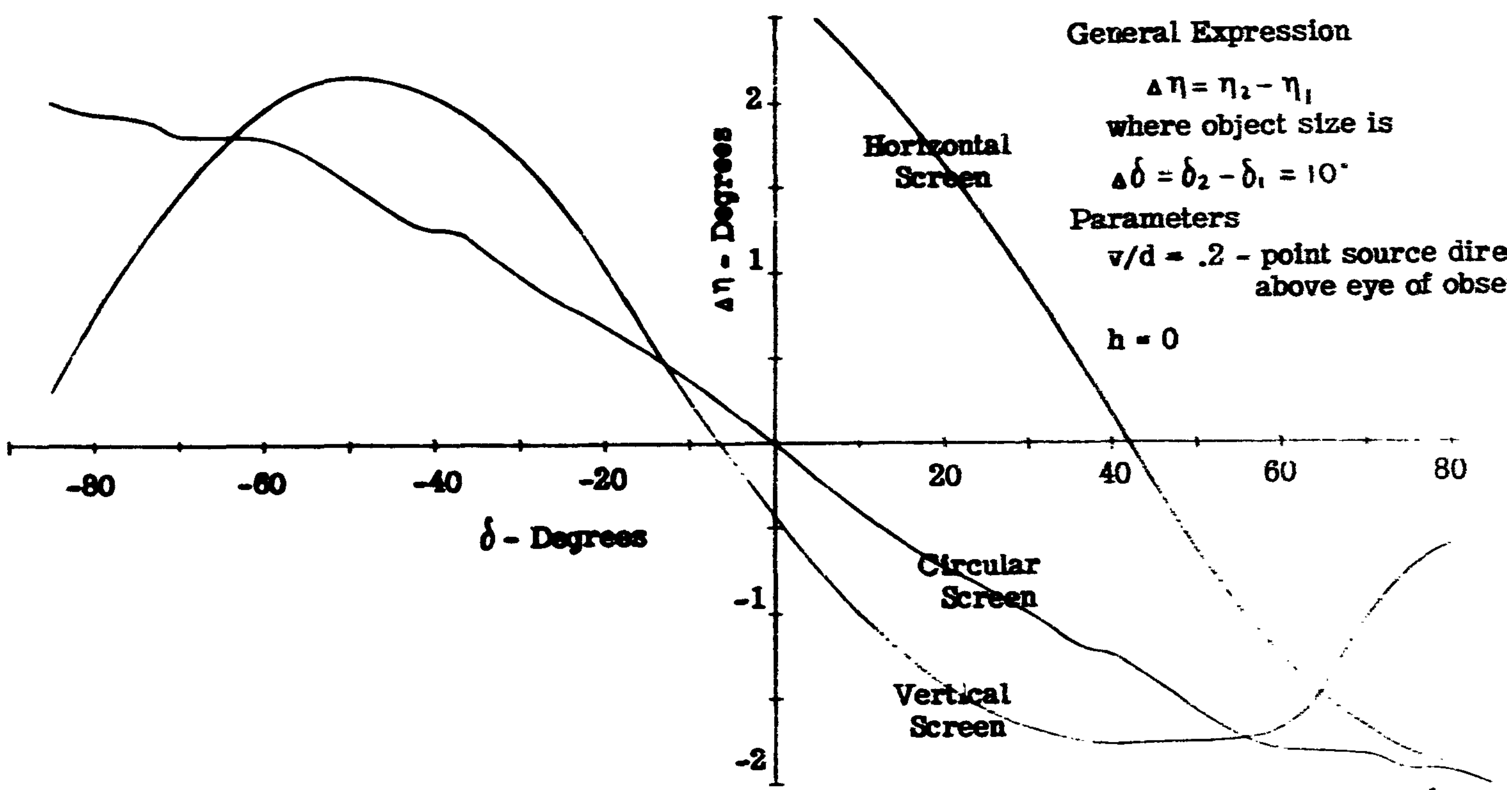
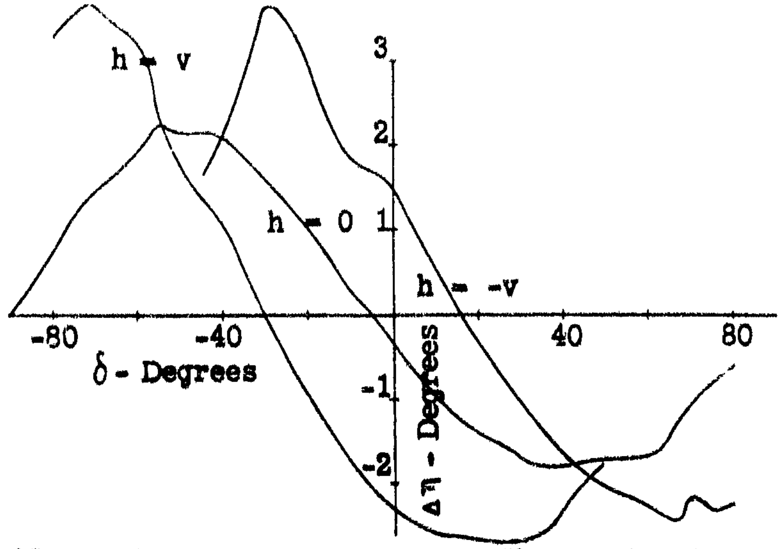
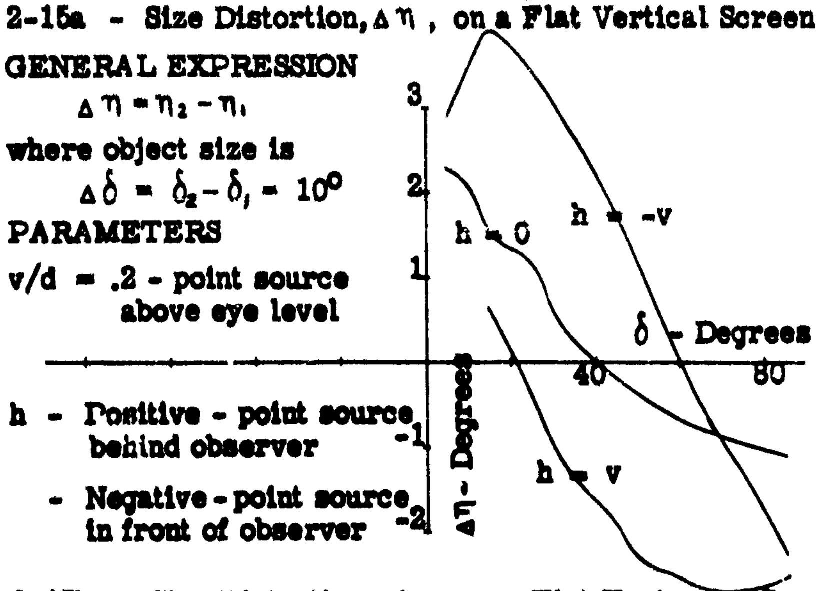


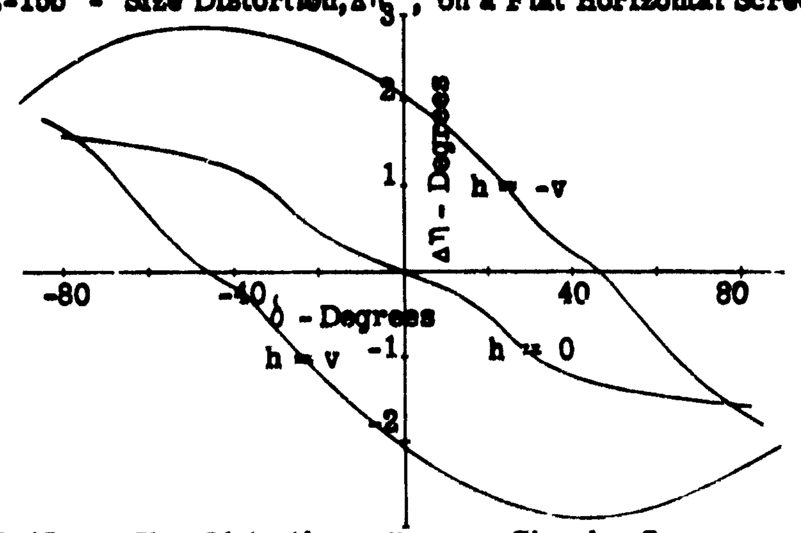
Figure 2-14 - Size Distortion, $\Delta\eta$, of a 10^{0} Object ($\Delta\delta = 10^{0}$) with Viewing Angle, δ, on Three Basic Screen Shapes with Selected System Parameters



2-15a - Size Distortion, $\Delta\eta$, on a Flat Vertical Screen



2-15b - Size Distortion, $\Delta\eta$, on a Flat Horizontal Screen



2-15c - Size Distortion, $\Delta\eta$, on a Circular Screen

Figure 2-15 - Size Distortion, $\Delta\eta$, of a 10^0 Object ($\Delta\delta = 10^0$)

the object approaches or departs from the viewer. If an object is viewed in the distance ($\delta \approx 0$) and it approaches the viewer ($\delta \rightarrow 90^{\circ}$), the size of the object should change uniformly in a specific manner to give the proper illusion of speed. A departure from this rate of change in size gives the unrealistic impression that the object is moving particularly slow or fast. Figure 2-16 shows the rate of change of size distortion with viewing angle for an object 10° in size when v/d is equal to .20 and h is equal to 0.

2.4.17 Again an example will best illustrate the use of these curves. If an object traveling towards the observer ($\delta = 0$ to $\delta = 90^{\circ}$) is seen at a viewing angle of 60° below the horizontal on a flat vertical screen, it appears to move .03T slower than is actually the case (where T is the angular velocity $d\delta/dt$ defined by the speed of the display-object and the dimensions of the system). Positive values of velocity distortion mean that the object appears to move slower than is actually the case, while negative values have the opposite effect.

2.4.18 Since the curves in figures 2-11, 2-12, 2-13, and 2-16 provide cues to velocity distortions, the slope of these curves provide a measure of acceleration distortion. Regions where the slope of these curves is sharp, indicates areas when acceleration distortion is great and may be disturbing and distractive to the observer.

2.4.19 These studies indicate not only the magnitude and effect of distortion due to displacement of the eye from the point source but also indicate that in a problem where the visibility angle is defined (for example, from 40° above to 40° below the horizontal) it is possible to minimize distortion by adjusting the system geometry including screen shape. In this process, however, the ratio v/d should be held as low as possible. The value of d is limited by the space limitations imposed on the design of the projection system.

2.5 Distortion Due to Screen Curvature, Rear Projection System

2.5.1 As previously pointed out, (paragraph 2.2.1) if the screen used with a rear screen projection system is curved about the observer to achieve a wide angle of projection, distortions are introduced in the display-image because the projection distance increases while the viewing distance remains constant (figure 2-3c). This distortion is caused entirely by curving the screen and is independent of the eye to screen distance and of the point source to screen distance provided these two distances are equal. Position distortion, η, due to curving the screen

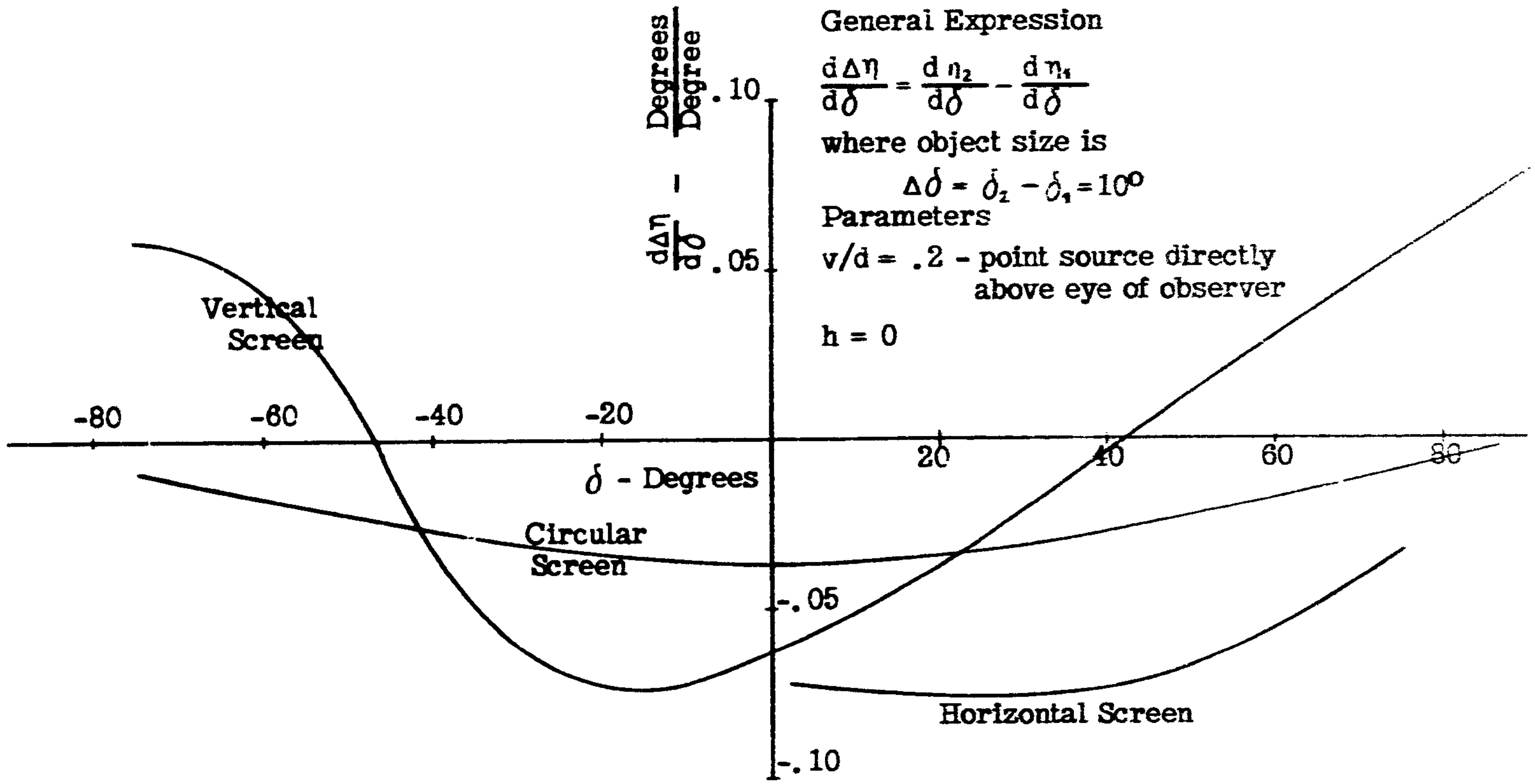


Figure 2 - 16 - Rate of Change of Size Distortion, $d\Delta\eta/d\delta$, of a 10^{o} Object ($\Delta\delta = 10^{o}$) with Viewing Angle, δ, on Three Basic Screen Shapes with Selected System Parameters

about the eye of the observer is plotted in figure 2-17a for the full range of viewing angles, δ. This distortion occurs when the screen is curved from the observer's left to his right as well as when it is curved from above the observer to his feet. When the curvature is compounded (spherical screen) the distortions are compounded. Note that the distortions are small with small viewing angles from the "straight forward" viewing angle but increase sharply when the viewing angle is greater than 30^o from the "straight forward" viewing angle. The rate of change of position distortion, $d\eta/d\delta$, with this projection system is illustrated in figure 2-17b. This rate furnishes a clue to velocity distortion. Note that the rate is small where the distortion is small and it is large where the distortion is large. The rate of change of this velocity, the slope of the curves in figure 2-17b, is a cue to acceleration. In the area where position distortion is small acceleration distortion is small. When viewing angle exceeds 15^o to either side of the "straight forward" position the slope of the curve is constant and acceleration distortion is constant.

2.6 Factors Effecting Resolution and Definition of the Display-Image

2.6.1 Good resolution and definition are important qualities of any image. An image with good definition is sharp and clear with distinct demarcation between details, whereas one with poor definition is blurred. An image with good resolution presents fine details as separate individual objects, whereas one with poor resolution presents details running into one another and not separable into individual obje(.* In a projection system, the degree to which the resolution and definition of the display-image approach the resolution and definition of the display-object may be termed the resolving and defining power of the source and is an important criterion for evaluation of the system. Resolution and definition are very closely allied. Indeed, the resolving power of a projection system is usually limited because of deterioration in definition. As the edges of adjacent lines become more blurred, each individual line loses its identity and merges into one blurred image.

2.6.2 In the point source projection system, definition of the display-image depends primarily on the source diameter to display-object line width ratio, P_1, on the point source to display-object distance, a, and on the effects

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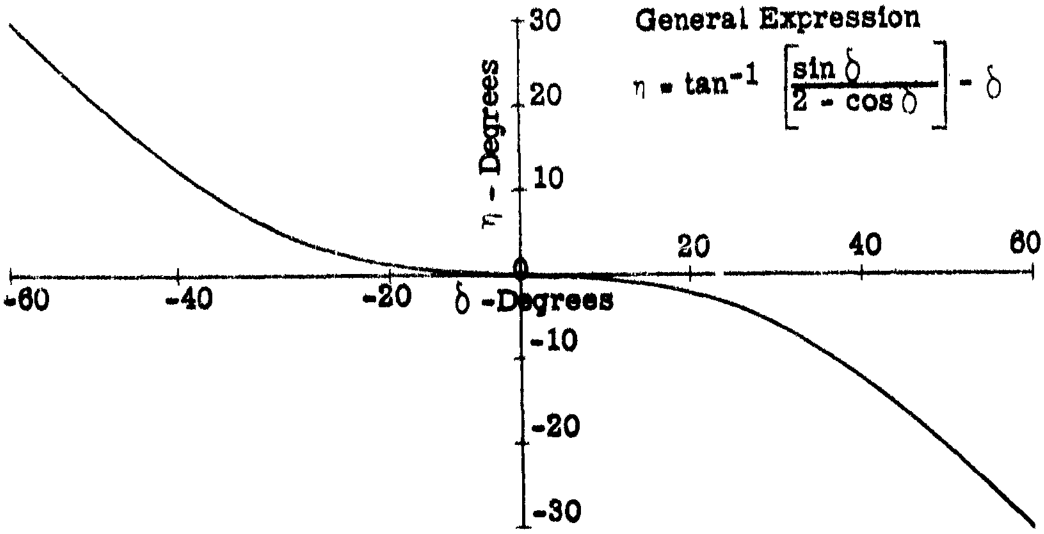
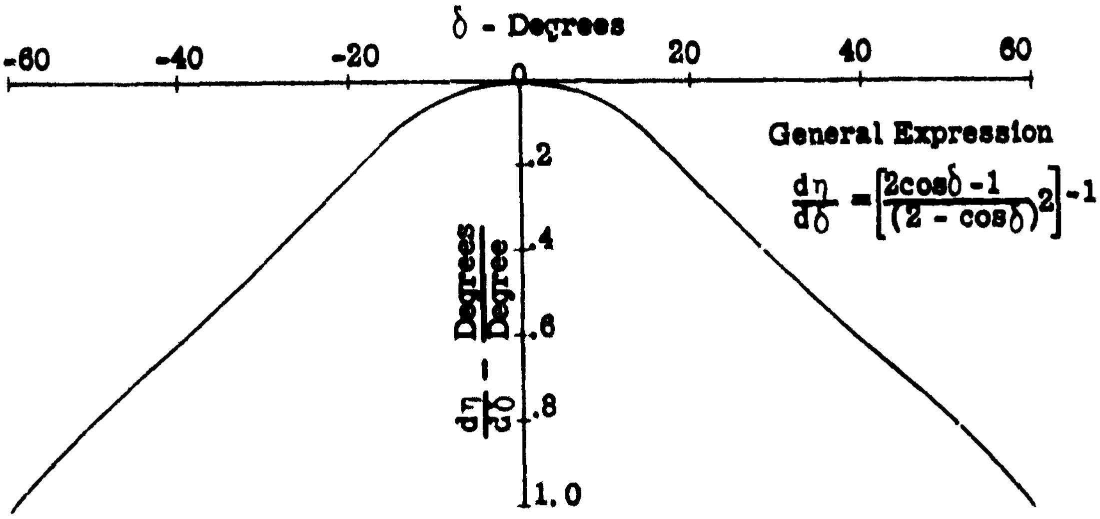
* Resolving power is often measured by the number of lines per unit width of a regular pattern of opaque lines on a transparent background which can be individually distinguished. The greater the number of lines, the greater is the resolving power of the system.



2-17a - Position Distortion, η, at Viewing Angle, δ



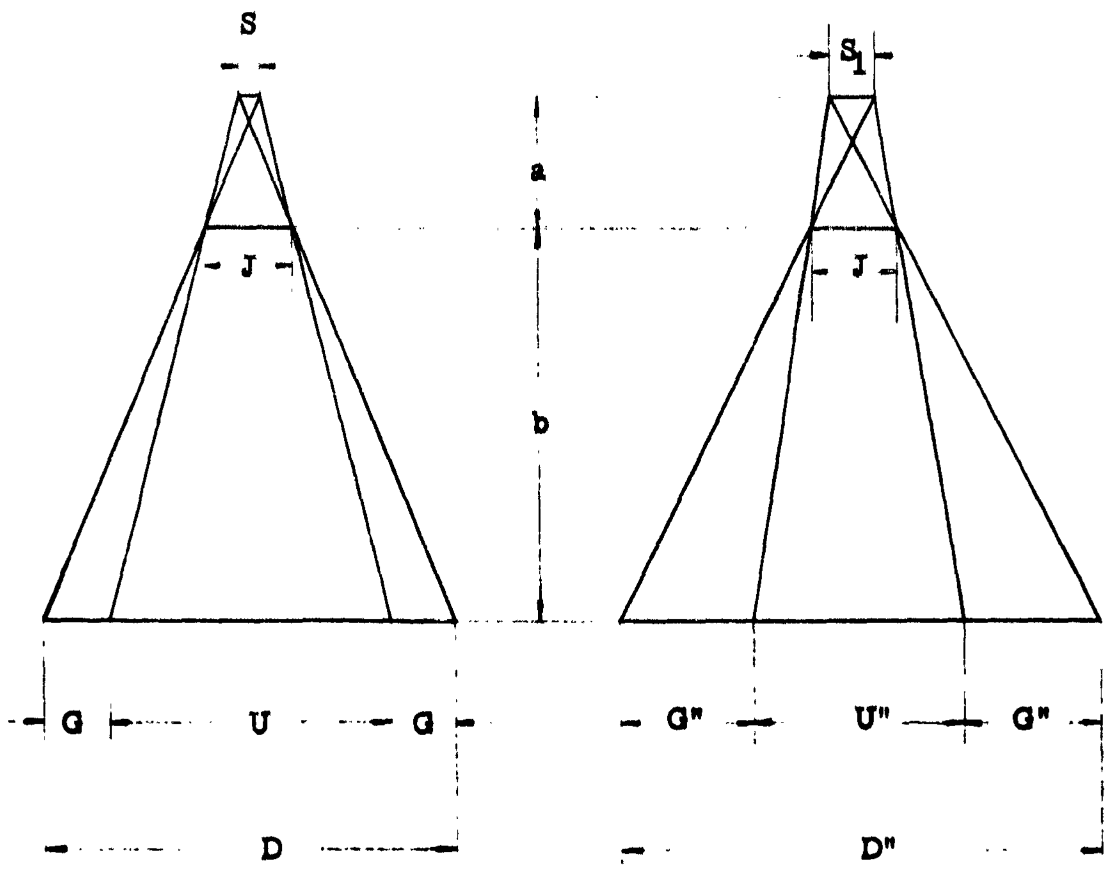
2-17b - Rate of Change of Position Distortion, dη/dδ, at Viewing Angle, δ

Figure 2-17 - Position Distortion - Rear Projection, Curved Screen

of diffraction. Resolution depends primarily on the source diameter to display object line width ratio, and on the effects of diffraction.

2.6.3 By far the most important factor affecting resolution and definition is the size of the extended source; that is, any source which departs from a geometric point source. The projection of an opaque line of finite width by a geometric point source yields a well defined magnified image which is totally black on an illuminated background. Use of an extended source results in deterioration in the sharpness of this image. Each element of the extended source acts as a geometric point source and the over-all effect is to enlarge the image of the line, reduce the totally black area (the umbra) and cause a gray area (the penumbra) on both sides of the umbra as shown in figure 2-18. The penumbra is a gray area graduating from totally black immediately adjacent to the umbra to totally white immediately adjacent to the illuminated background. The larger the source (assuming a constant display-object line width) the smaller is the ratio of umbra to penumbra-plus-umbra, P". As this ratio decreases, image definition deteriorates until finally it becomes impossible to differentiate between the umbra and the penumbra. At this point the projected display-image is enlarged beyond the theoretical magnification (magnification with a geometric point source) and the display-image contrast is considerably reduced from the possible maximum.

2.6.4 The display-object line width may accentuate the effects of the extended source. As the display-object line width decreases and approaches the extended source diameter, it is clear from figure 2-19 that the umbra becomes a smaller and smaller portion of the total image width. When the display-object line width becomes less than the extended source diameter the umbra gradually disappears and only a gray display-image remains. Figure 2-20 illustrates the extent to which the use of an extdnded source enlarges the display-image line width over and above the theoretical magnification. It also shows that when theoretical magnification exceeds 10, further increase in theoretical magnification has little effect on display-image definition. These curves are plotted for selected values of the ratio of the extended source diameter to the display-object width, P_1. The relative increase in the extended source projected image size over the geometric point source projected image size, P', with theoretical magnification is plotted in accordance with equations derived in Appendix II. Note that as the extended source diameter approaches and exceeds the display-object line width (P_1 greater than 1), the display-image becomes greatly enlarged above the theoretical magnification. Indeed, for a P_1 value of 2, the image size is twice the theoretical for a magnification of 2.



By definition $S_1 > S$. If a, b and J are held constant it can be easily shown by similar triangles that

$$U'' < U$$

$$D'' > D$$

$$G'' > G$$

Figure 2 - 18 - Schematic Showing Effect of Different Source Diameters, S and S_1, on Display-Image Quality.

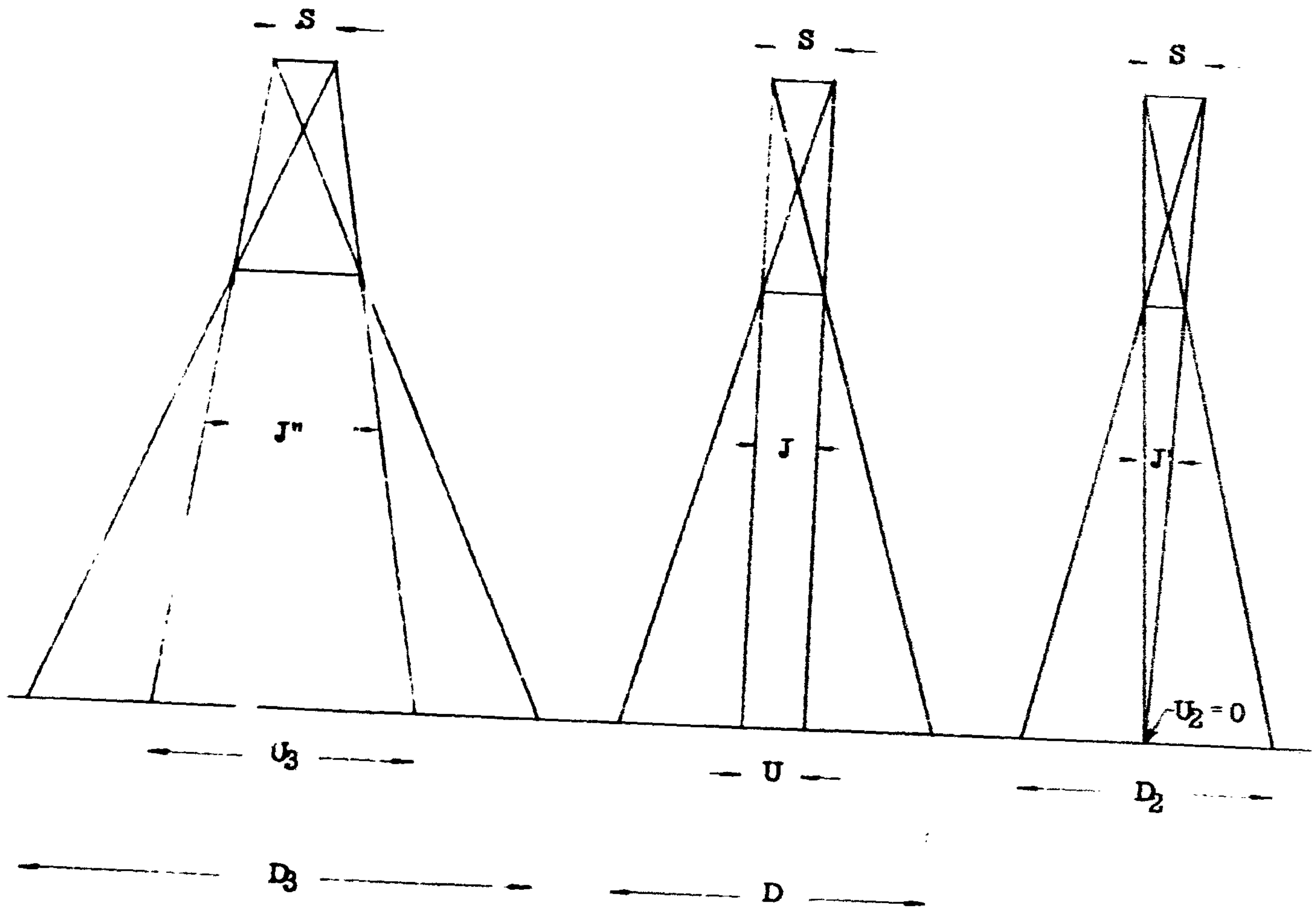


Figure 2 - 19 - Schematic Showing Effect of Reducing Display-Object Line Width, J, on the Umbra, U, of the Display-Image, D.

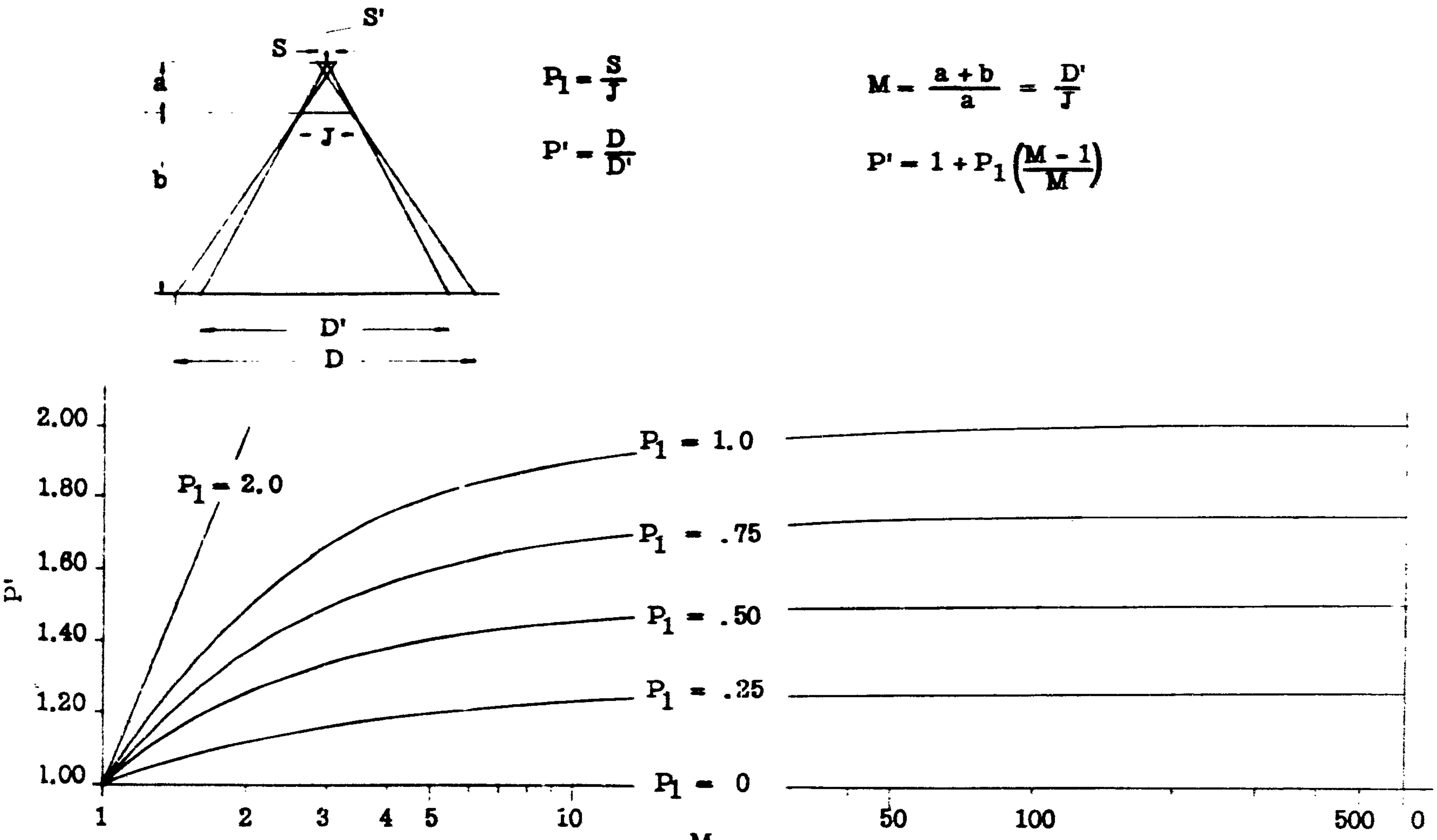


Figure 2-20 - Enlargement P' of Display-Image Width With Magnification M Due to Use of an Extended Source $S(P_1 > 0)$ Rather than a Geometric Point Source $S'(P_1 = 0)$.

2.6.5 The extent to which the ratio of umbra to total display-image area, P", decreases with an extended source is illustrated in Figure 2-21. These curves are plotted for selected values of P_1 and compare the behavior of the ratio P" with changes in theoretical magnification from equations derived in Appendix I. Note that as P_1 approaches and exceeds 1 the umbra decreases sharply so that when P_1 equals 2 with a theoretical magnification of 2 there is no umbra. Here the image is entirely gray and is not easily recognized.

2.6.6 The above theoretical curves mean that details on the display-object must be represented with wide lines relative to the source diameter even at the risk of exaggeration in order to achieve satisfactory definition. It is important that the ratio P_1 be minimized and certainly should not exceed unity. It is preferable not to use values of P_1 greater than 0.5.

2.6.7 Experimental confirmation of this rule is presented in figures 2-22, 2-23, 2-24 and 2-25. These curves represent the subjective impressions of three observers who viewed static scenes consisting of projections of hand decorated display-objects or photographic display-objects. Two different light sources were used: the 25 watt hafnium concentrated arc lamp (.013" source diameter), and the 2 watt zirconium lamp (.004" source diameter). Figure 2-22 illustrates the impressions of the observers with the combination of the 25 watt hafnium lamp and several hand decorated transparent display-objects. These transparencies consisted of the same scene made to different scales: 500:1, 1000:1, and 2000:1. The source to display-object distance was varied and the observers were asked to render an opinion of the static display-image quality by classifying each as "good, satisfactory, marginal or poor". While the curves represent the average of the opinions, these did not differ appreciably. Note that the curves in Figure 2-22 appear to be in close agreement. For source to display-object distances greater than 2" the display-image is good or satisfactory. However, below the 2" distance the image tends to deteriorate. The curves are similar because the display-object line width did not differ appreciably in spite of the different scales of the objects.

2.6.8 The curves in Figure 2-23 were obtained in the same manner except that photographic display-objects were used with the 25 watt hafnium lamp. Here again the same scene was depicted at several different scales. In this instance a marked deterioration in display-image quality occurred at lamp distances between two and four inches, depending on the scale ratio of the photograph. Quality deteriorates more

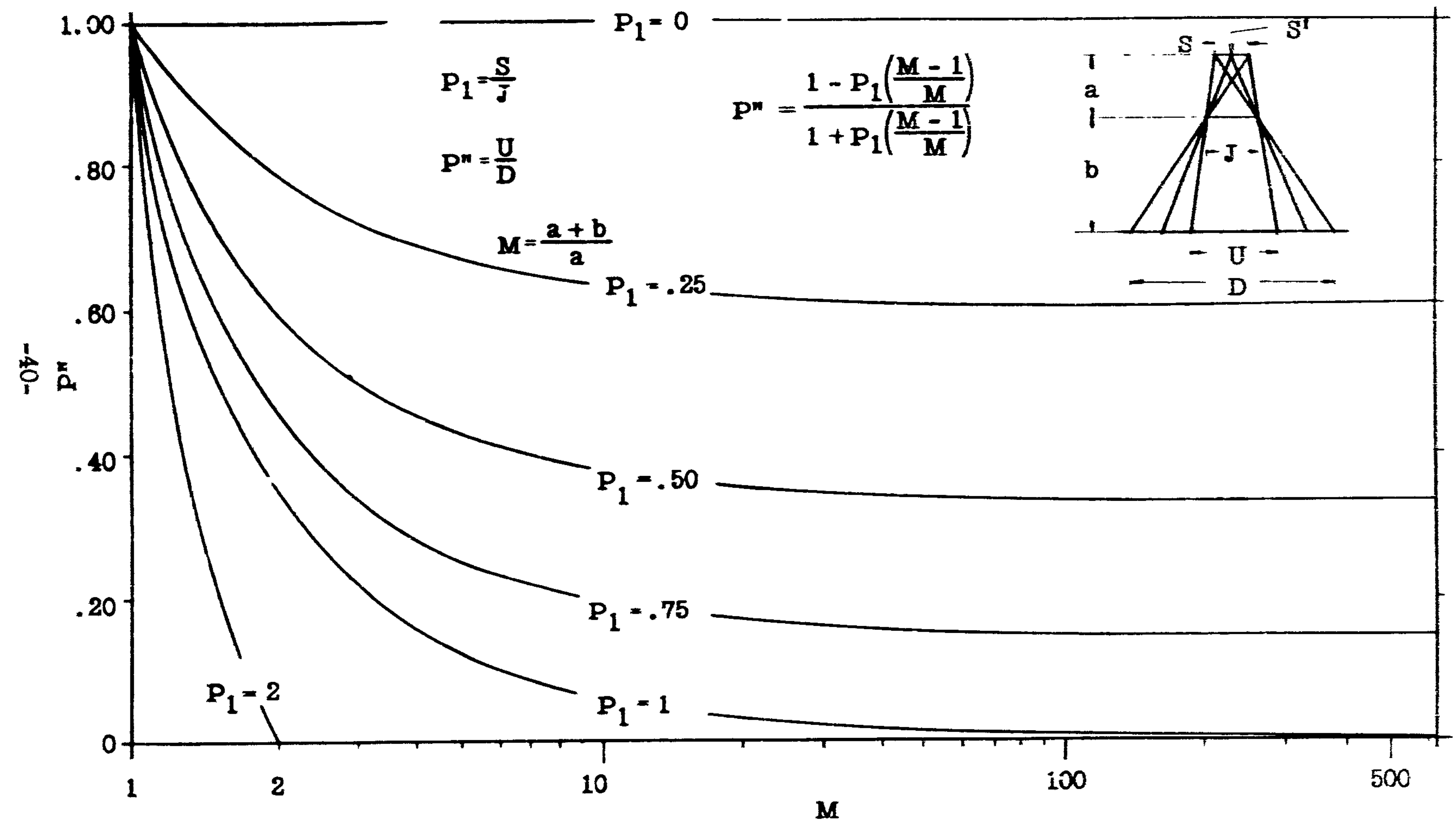


Figure 2 - 21 - Quality of Resolution and Definition P" as Affected by Magnification M and by Source Size to Display-Object Line Width Ratio P_1.

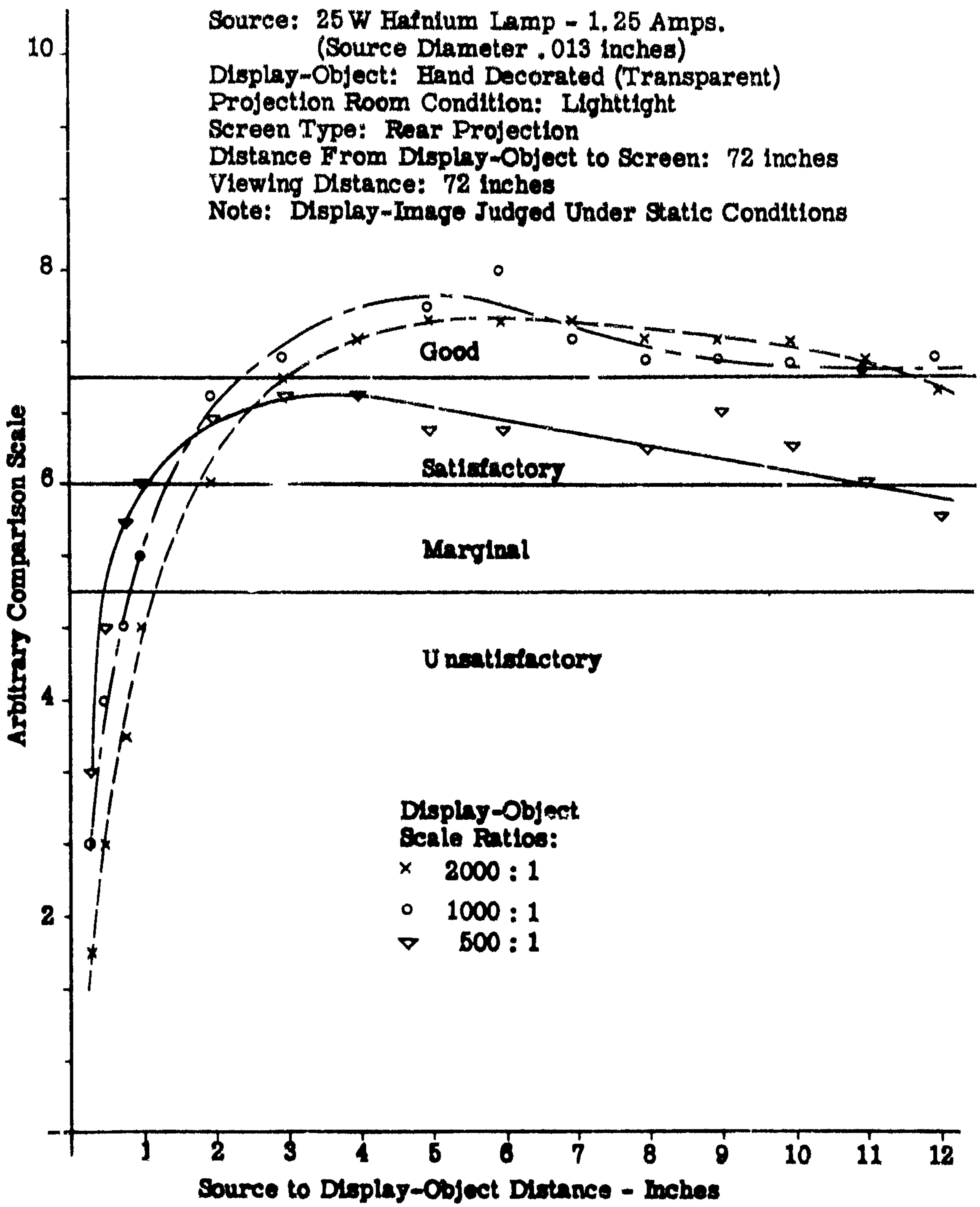


Figure 2-22 - Subjective Evaluations of Display-Images Produced by Projecting a Hand Decorated Display-Object With a 25 Watt Hafnium Lamp.

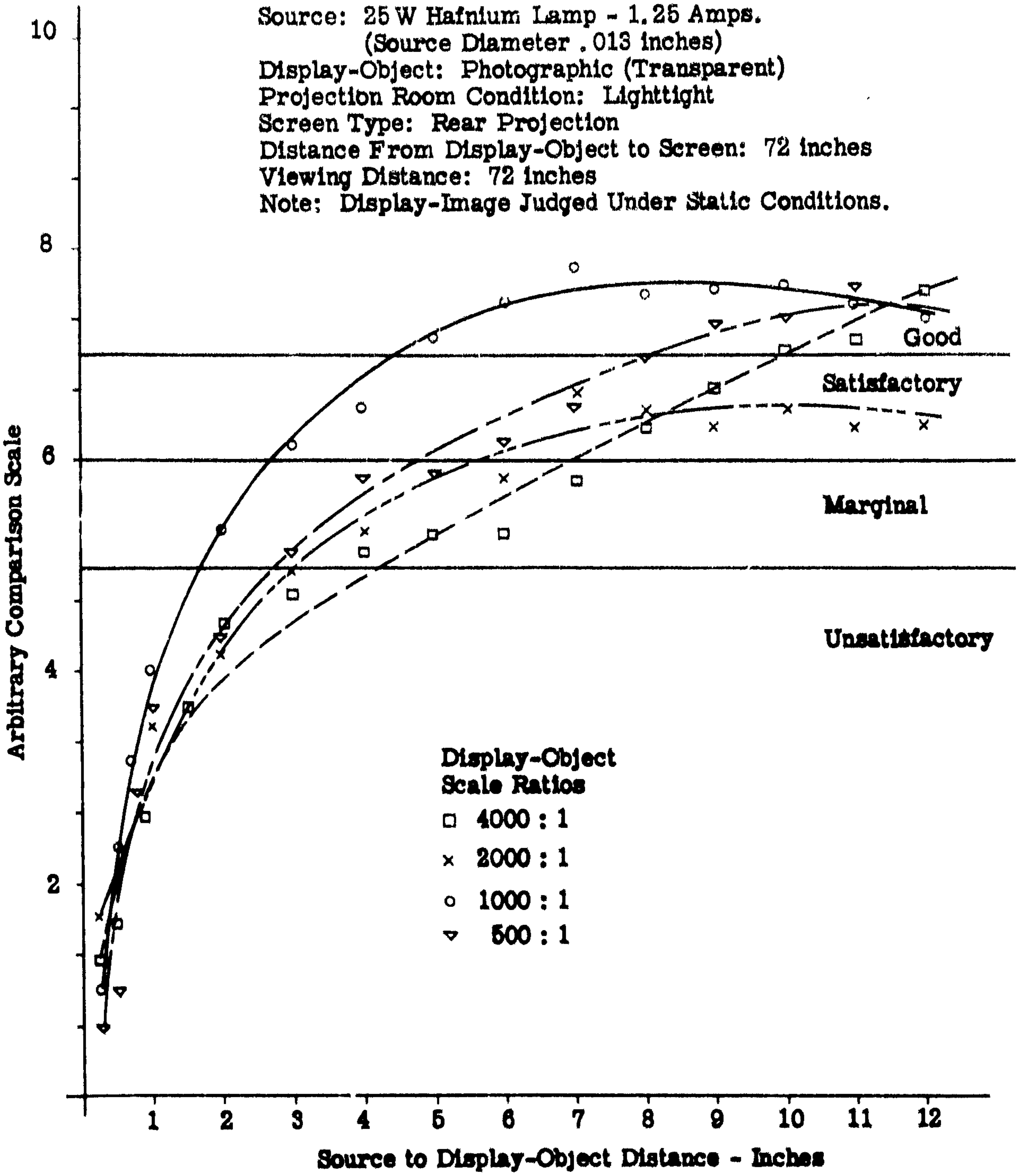


Figure 2-23 - Subjective Evaluations of Display-Images Produced by Projecting a Photographic Display-Object With a 25 Watt Hafnium Lamp.

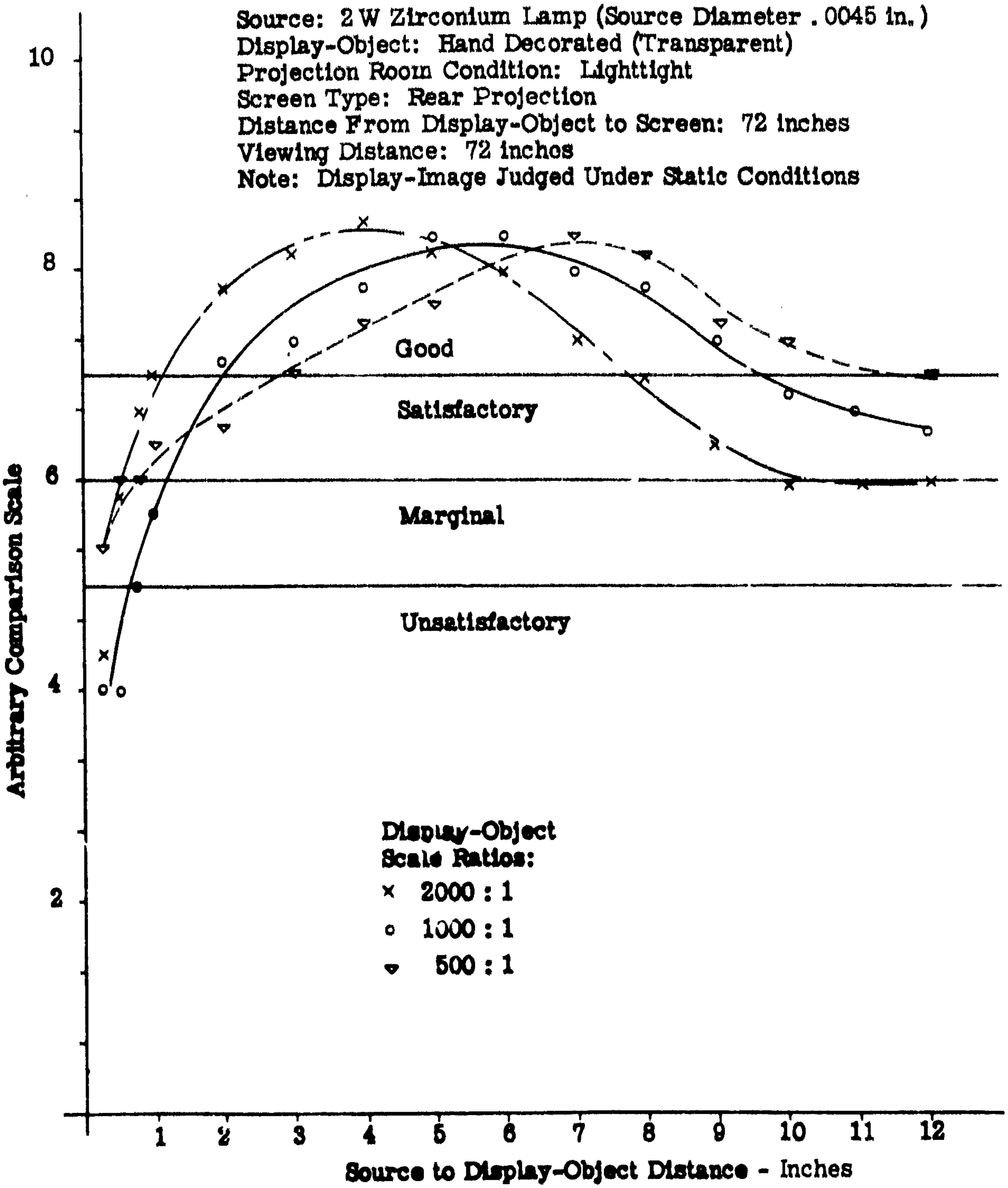


Figure 2-24 - Subjective Evaluations of Display-Images Produced by Projecting a Hand Decorated Display-Object With a 2 Watt Zircenium Lamp.

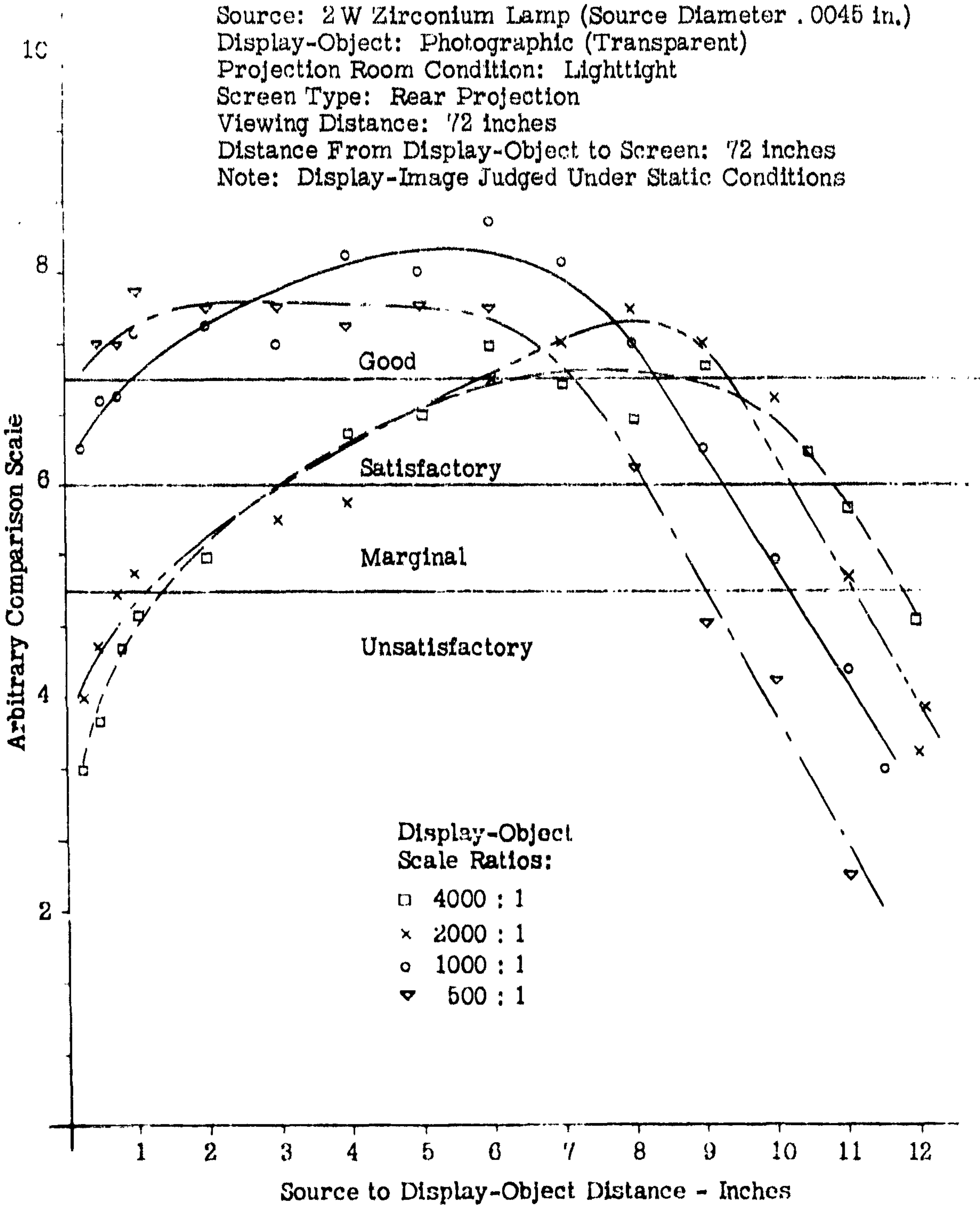


Figure 2-25 - Subjective Evaluations of Display-Images Produced by Projecting a Photographic Display-Object With a 2 Watt Zirconium Lamp.

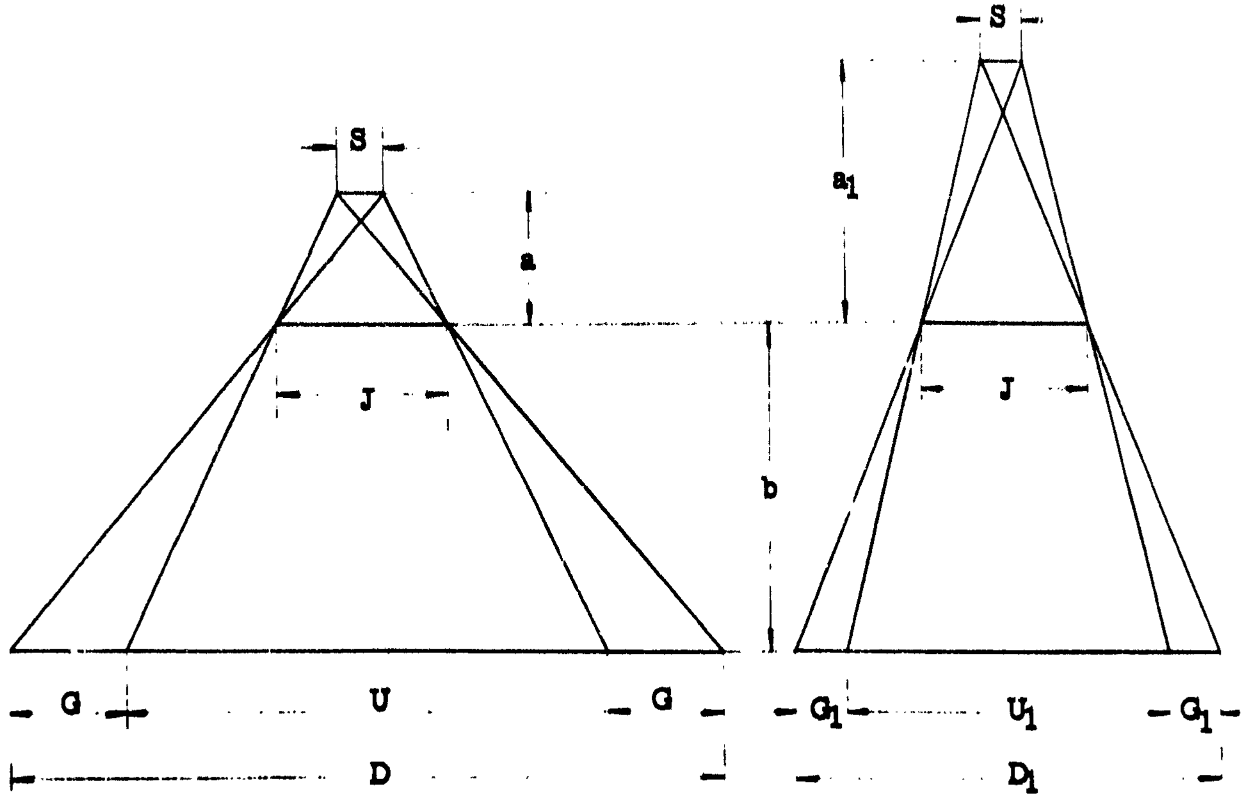
rapidly with larger scale ratios primarily because the P_1 value at high scale ratios is relatively large and therefore the display-image deteriorates rapidly at large magnifications. The large P_1 ratio results from the fine detail recorded on photographic film.

2.6.9 The curves in figure 2-24 were obtained using a 2 watt zirconium lamp as the light source and the same hand decorated transparent display-objects used to obtain figure 2-22. Note that for large theoretical magnifications, the quality of the display-image was considered superior to that obtained with the 25 watt hafnium lamp. This is directly attributable to the smaller source diameter and its effect on the ratio P_1. The poor image quality at low magnifications was not a result of poor image definition, but primarily results from a low level of screen illumination. The low light output of the 2 watt zirconium lamp projects the display-image at a screen illumination below the threshold level and, at low magnifications, the fine detail is then not easily distinguished. Screen illumination seriously affects impressions of display-image quality, especially if the illumination is near or below the threshold level. To a lesser degree, the deterioration of picture quality at low magnifications can be attributed to diffraction effects as described in paragraph 2.7.

2.6.10 The photographic display-objects used to obtain figure 2-23 were projected with the 2 watt zirconium lamp to obtain the curves in figure 2-25. Here again the effect of the smaller diameter source is evident in the improved image quality. Indeed, with low scale ratios, the image quality is good at high magnifications since the photographic display-object appears more realistic than the hand decorated display-object. However, with large scale ratios varying between 2,000:1 and 4,000:1 the display-image deteriorates rapidly at high magnifications. This is explained by noting that the inherent nature of photography is to depict all details. At large scales, much detail is present on the display-object as fine line work and minute areas of color. Any of these lines or areas smaller than the source diameter is lost when a magnification of 10 is reached. Each remaining detail on the display-image must result from details on the display-object larger than the point source diameter. Nevertheless as the magnification increases, the total blurred area of the screen increases, because the blurred images of no longer defined fine details reinforce one another and destroy the definition of larger details. With much detail present, the whole image rapidly loses its basic characteristics and becomes an indistinguishable mixture of color blends. The deterioration at low magnification is again the result of poor screen illumination and diffraction.

2.6.11 A second important factor limiting resolution and definition of the display-image is the point source to display-object distance. The importance of this factor derives directly from the effects of an extended source on the display-image. It will be recalled that the use of an extended source reduced the umbra of the display-image and causes a penumbra to be projected on both sides of the umbra. If the extended source diameter and display-image line width are held constant, the ratio of umbra to total display-image area decreases as the source to display-object distance decreases. This phenomenon is illustrated in figure 2-26. Figure 2-27 shows the effect of varying the source to display-object distance on the image quality for selected values of source diameter. The curves in this figure are plotted from expressions derived in Appendix II, using angular definition as an objective measure of image quality. This objective measure of image quality has been correlated with subjective evaluations of image quality using the data available from figures 2-22, 2-23, 2-24 and 2-25. Two assumptions underlie figure 2-27: (1) two adjoining areas of different colors are projected by a source of finite diameter; (2) the observer is very close to the projection source. Upon projection, an "area of demarcation", separates the two color areas on the display-image rather than the distinct line of demarcation which separates the color areas on the display-object. The "area of demarcation" increases with magnification and is also a linear function of source diameter. As seen by the observer, the area of demarcation subtends an angle in spac which may be termed angular definition.

2.6.12 The curves in figure 2-27 can be of value in determining the minimum source to display-object distance which will give an acceptable display-image when using any particular diameter source. Conversely when it is desired that the source approach the display-object within some particular minimum distance, the largest source diameter which will give acceptable display-image quality can be determined from these curves. When used in this manner it must be remembered that these curves are based on the following conditions: (a) The P_1 ratio is less than 1 for the majority of the details; (b) the display-image quality is judged statically; (c) the projection is normal to the screen and is viewed normal to the screen; (d) the source to display-object distance is the minimum distance measured normal to the display-object plane. It should be noted that when the angle of projection deviates from the normal to the display-object plane, the source to display-object distance increases as the secant of the angle between the normal and the angle of projection in question. Thus when a large display-object area is projected by a point source of light, details on the display-object remote from a point directly beneath the point source may be projected with good definition even



By definition $a < a_1$. If S, b and J are held constant, it can easily be shown by similar triangles that

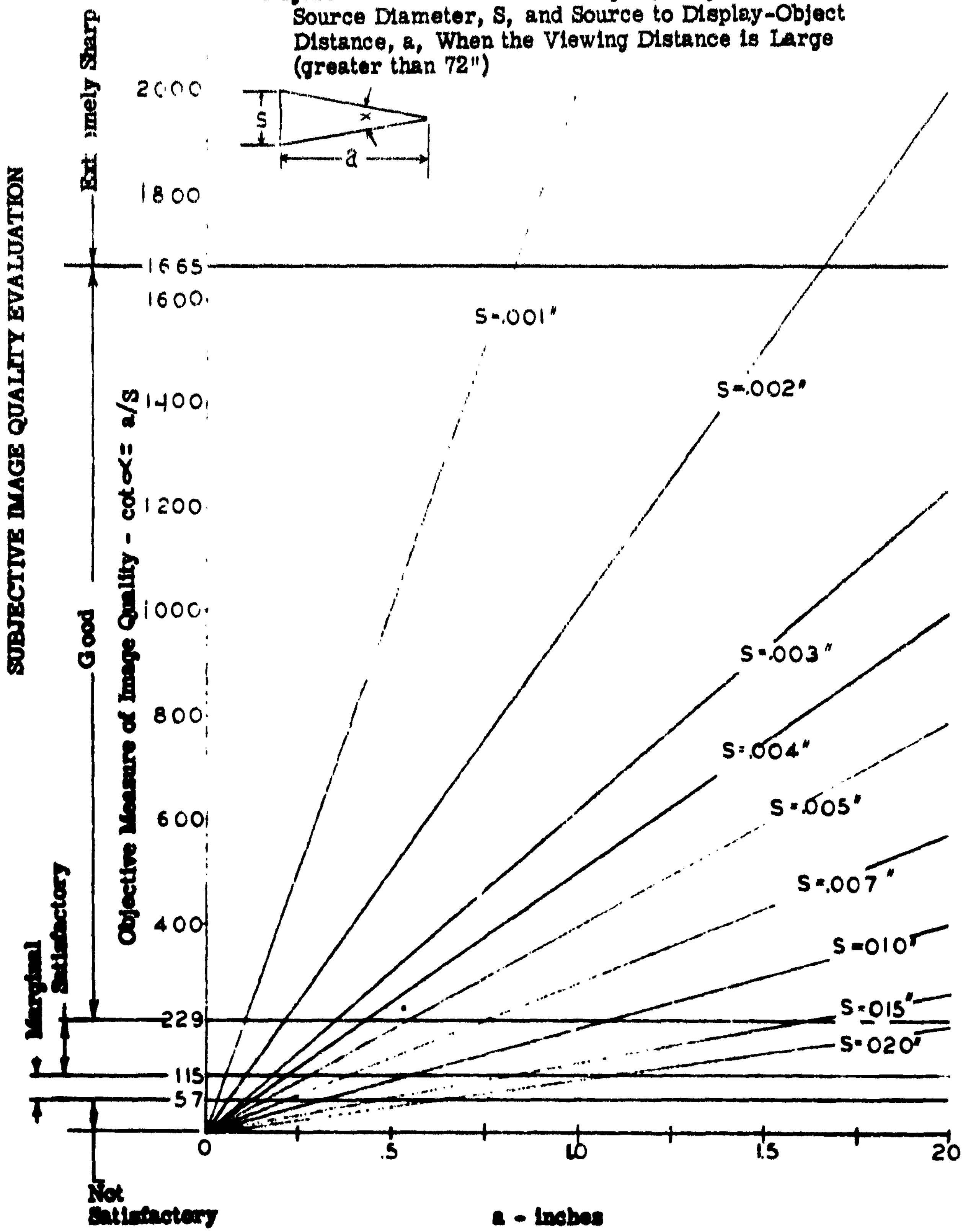
$$U > U_1$$

$$G > G_1$$

$$D > D_1$$

Figure 2 - 26 - Schematic Showing Effect of Source to Display-Object Distance on Display-Image Quality

Figure 2-27 - Relation of Image Quality to Extended Source Diameter, S, and Source to Display-Object Distance, a, When the Viewing Distance is Large (greater than 72")



though details immediately beneath the point source may be projected as a blur. When the display-object is a terrain presentation, this means that the near scenery will be blurred but that distant scenery will be presented clearly, conditions which may be satisfactory for certain training problems. It must be appreciated, therefore, that information obtained from Figure 2-27 should be modified to suit the type of display-object used, the projection conditions, and the display-image requirements of the problem.

2.7 Effects of Diffraction on the Display-Image

2.7.1 A very subtle and usually troublesome consequence of the wave nature of light is diffraction, that is very slight spreading of a beam of light as it passes over an opaque object. The wavefront, on striking the edge of an opaque object, creates secondary wavelets which can be considered as eminating from the edge of the opaque object and which spread out in all directions. Indeed, the light appears to bend around the edge of the opaque object. These wavelets interfere with or reinforce the major wavefront and result in alternate dark and light bands in the vicinity of the projected umbra edge as in Figure 2-28. Within the umbra light bands of diminishing intensity can be noticed while in the bright area dark bands appear. The over-all effect is to reduce the image definition because the alternate light and dark bands occurring along the edge of the projected image make it difficult to distinguish the edge.

2.7.2 Diffraction effects are not a function of size of the source but are influenced primarily by the source to the display-object distance, the display-object line width, and the wave length of light. Diffraction would be the factor limiting the resolution and definition of the display-image projected by a geometric point source of light. Since both diffraction and extended-source effects result in loss of definition of the display-image, it may be of interest to know which of these effects is most significant in a given instance. Equations defining the diffraction angle, γ, and the extended source angle, α, in terms of source to display-object distance, display-object line width, and the wave length of light are given in Appendix III. These equations are derived by considering the display-object line in the same nature as a slit, and by assuming the point source to display-object distance to be very large in comparison with the display-object line width.

2.7.3 The curves in Figure 2-29 show the effects of source to display-object distance on diffraction angle, γ, and on extended source angle,

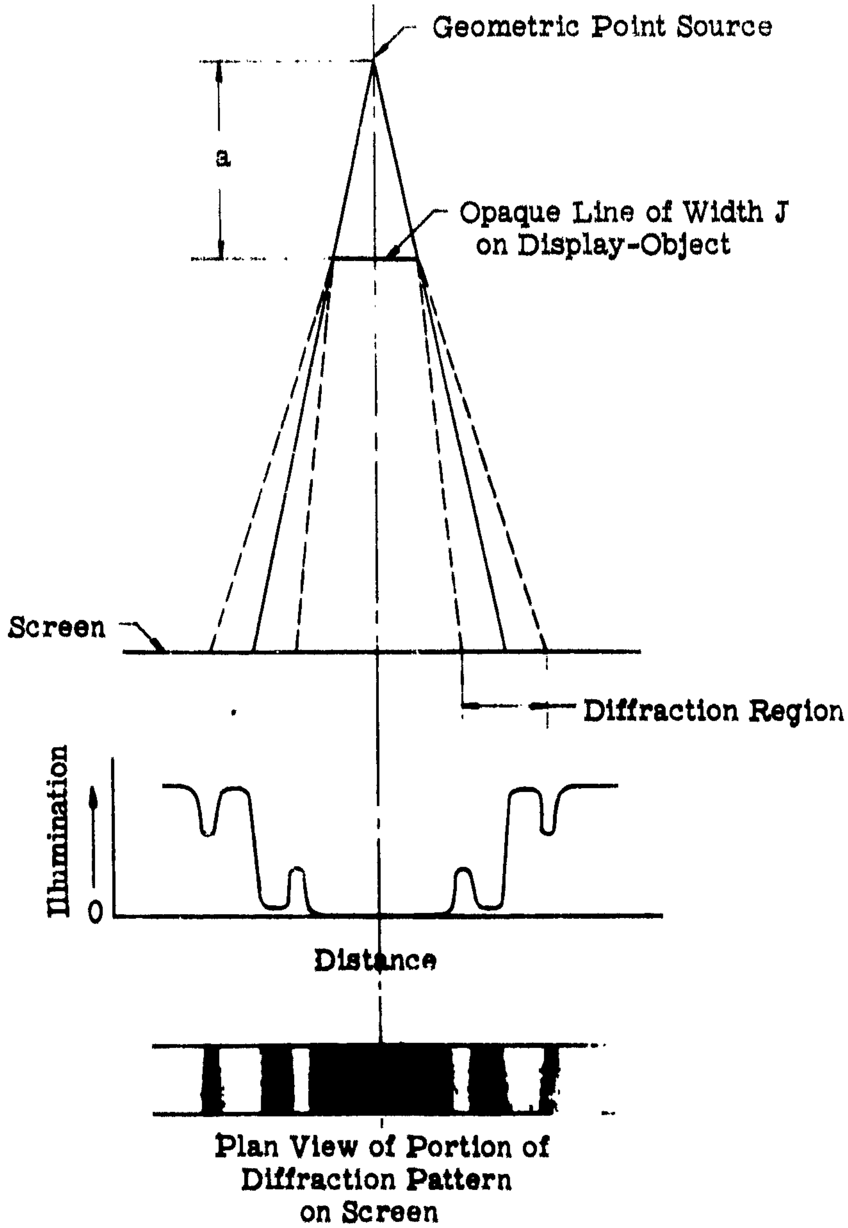


Figure 2 - 28 - Schematic Diagram of Diffraction Pattern Formation When Opaque Line of Finite Width J is Projected by a Geometric Point Source of Light

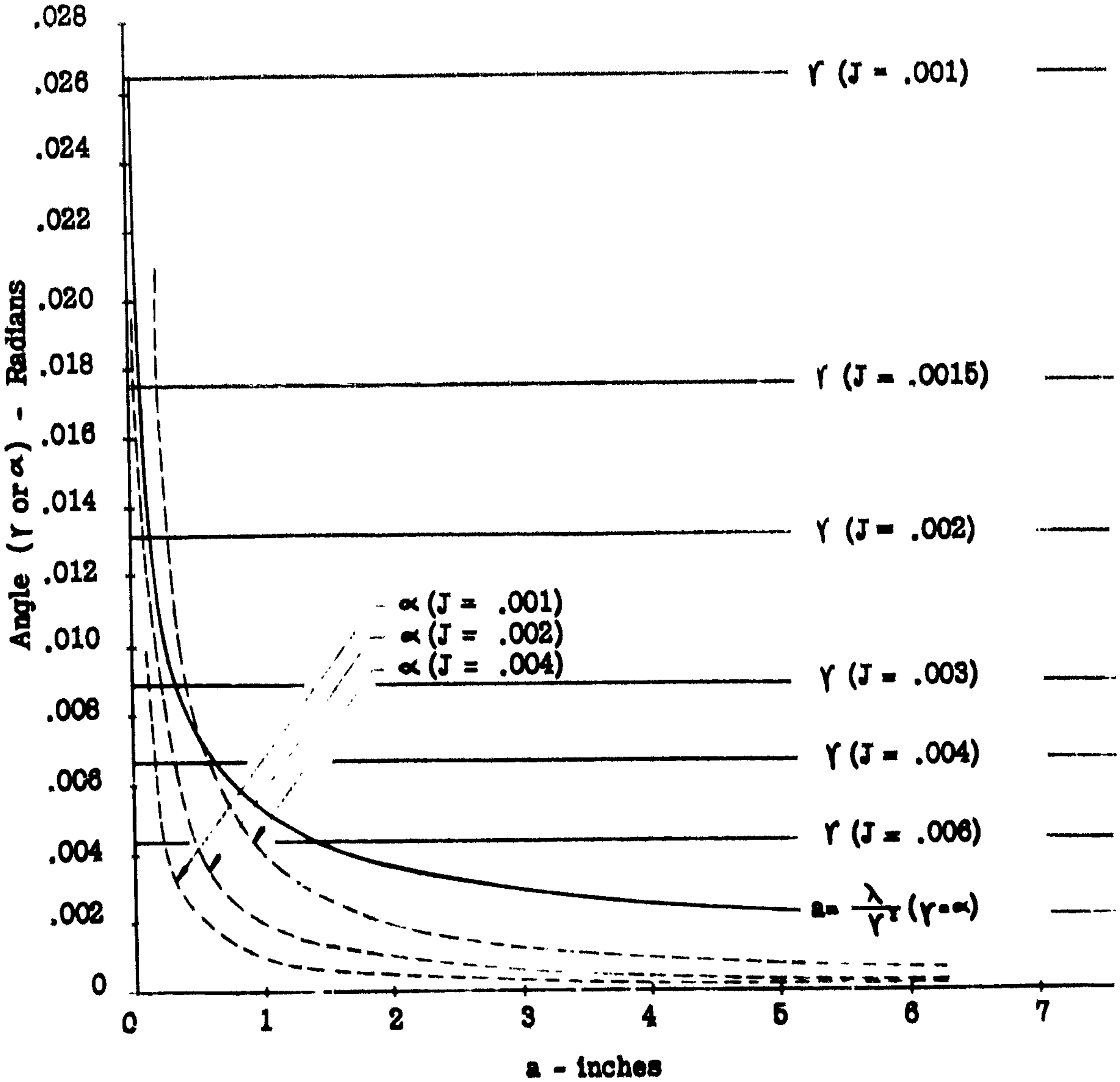


Figure 2 - 29 - Effect of Diffraction Angle, γ, on Display-Image Quality Compared with Effect of Extended Source Angle, α, on Display-Image Quality for Selected Display-Object Line Widths, J.

α, for selected values of display-object line width, J, when extended source diameter, S, equals J. The subjective image quality evaluations used in figure 2-27 have been super-imposed in figure 2-29. Thus for any combination of source to display-object distance and display-object line width, the expected display-image quality as well as the major cause of definition losses can be found from this figure.

2.7.4 The use of figure 2-29 is best explained by a few examples. If the source to display-object distance a, is held constant at 1" and the display-object line width, J, is allowed to assume different values, the intersection of the line, a=1", and the horizontal line representing the value of the diffraction angle, γ, at each value of J will determine the image quality. In addition, if the intersection falls above and to the right of the curve, a equals the wave-length of light, λ, divided by the square of the diffraction angle, γ, in radians, the major effect is diffraction; if it falls below and to the left of this curve the major effect is extended source. Thus, as J assumes values of 0.001, 0.002, 0.004, 0.007, the image quality is respectively unsatisfactory, marginal, satisfactory, and good. In the first three instances the major effect is diffraction; in the fourth, it is extended source.

2.7.5 The following conclusions can be drawn from the curves:

Values of J	.001	.0015	.002
Image Quality	Unsat.	Marg.	Marg.
Diffraction Effect	a >.0376	a>.0846	a > .1504
Extended Source Effect	a<.0376	a<.0846	a < .1504

Values of J	.003	.004	.006
Image Quality	Sat.	Sat.	Good
Diffraction Effect	a >.3384	a>.6016	a>1.3536
Extended Source Effect	a<.3384	a<.6016	a<1.3536

For all values of a, the projected image is unsatisfactory for values of J less than 0.0015, marginal for values of J between 0.0015 and 0.003, satisfactory for values of J between 0.003 and 0.006, and good for values of J greater than 0.006.

2.7.6 The effect of source diameter on resolution with source to display-object distance variation is illustrated in figure 2-30. Resolution evaluations were made from a display-image obtained by projecting a resolution chart as display-object with different size sources. The resolution chart, pictured in figure 2-31, is of the type used to test optical objectives. It consists of distinct opaque lines of various widths and spacings etched on glass. The lines are placed in groups, each group having very accurately held uniform line width and spacing. The groups are made to vary in regular sequence from a very coarse width and spacing to a very fine pattern. The display-image is examined to determine the group with finest spacing and line width (lines per mm) that can be easily distinguished.

2.7.7 The curves in figure 2-30 show the pronounced deterioration in resolution of the display-image as the source approaches the display-object when the source diameter is large (.017"). When the very small source diameter (.0045") of the 2 watt-zirconium lamp was used the limitation imposed on source to display-object distance by the lamp envelope was reached before any display-image deterioration was noted. Using the .017" diameter source, a resolution peak was obtained at a source to display-object distance of between 3 to 4 inches. This peak represents the point of best resolution where the effects of extended source and of diffraction are at a minimum. When the .0045 diameter source was used, no peak in the curve was obtained. At the smallest source to display-object distance physically obtainable the highest P_1 ratio measured was equal to 1. Presumbly, if the envelope restrictions were removed, and the source could be made to approach the display-object more closely, the resolution would reach a peak and would fall off as with the larger source diameter lamp. Deterioration in resolution to the left of the point of best resolution is caused by extended source effects and is very rapid at small source to display-object distances. The deterioration [illegible] occurs at distances beyond 4" is caused by diffraction. It is very [illegible] and appears to approach an asymptote well above minimum acceptable resolution levels. Hence, diffraction effects are not usually considered critical. It should also be noted from this figure that the effects of diffraction are independent of source diameter.

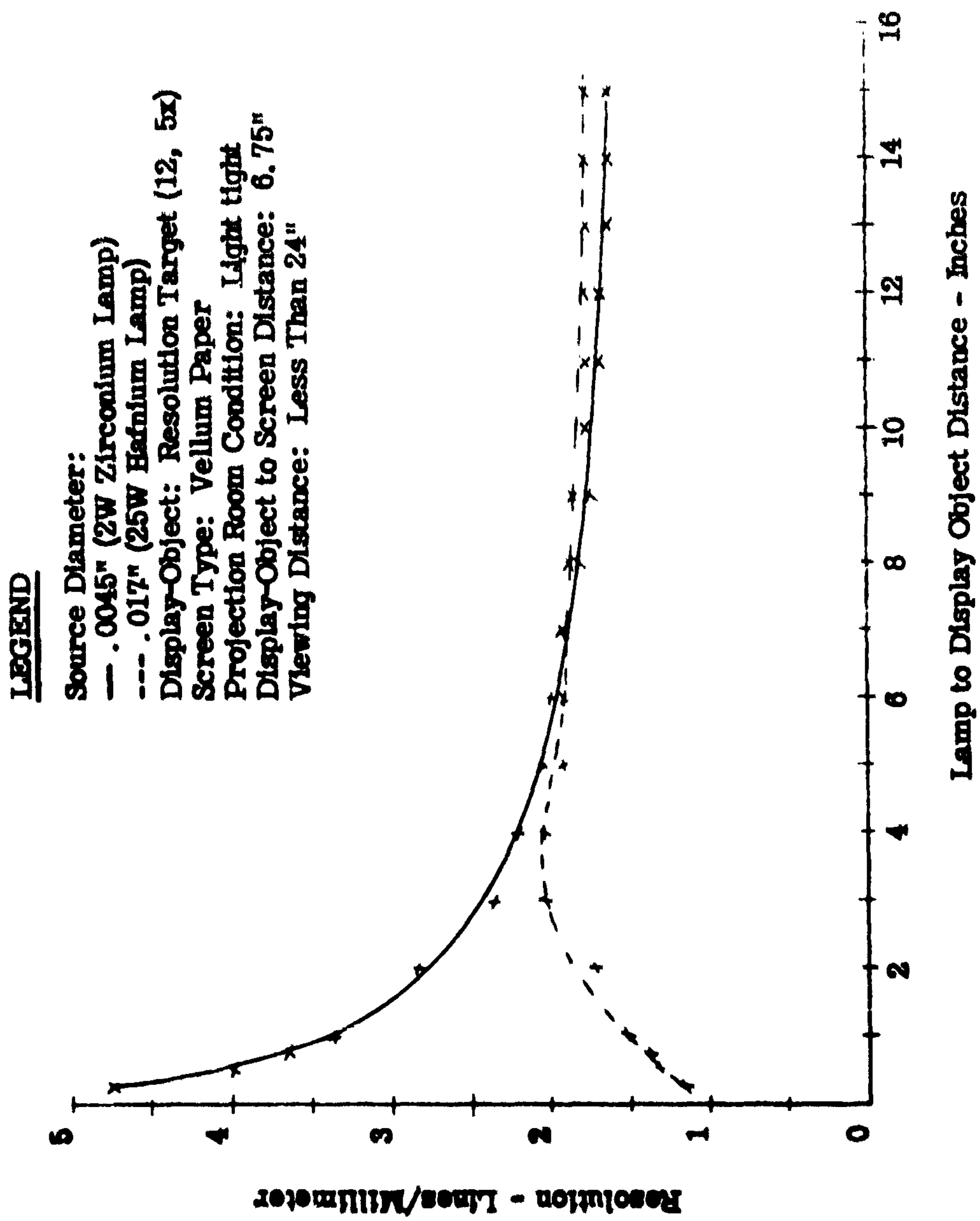


Figure 2-30 - Effect of Source Diameter on Resolution

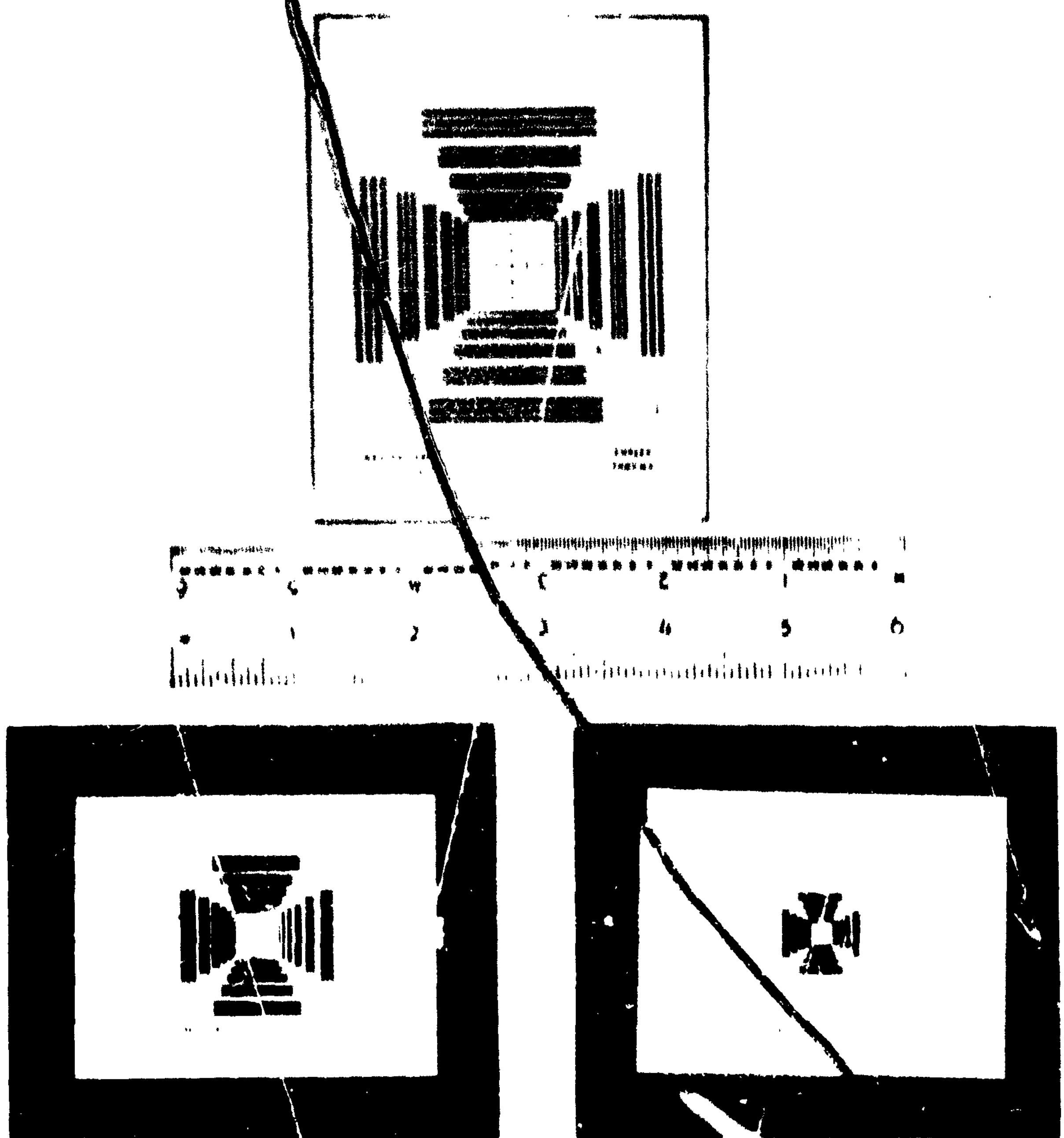


Figure 2-31 Resolution Patterns

CHAPTER 3

The Point Source of Light

3.1 Introduction

3.1.1 In the previous chapters the reader was made aware of the importance of the point source of light and its considerable influence on display-image definition. In this chapter the characteristics in a point light source which are desirable when used in the point light source projection system are discussed. The various types of sources which are available and applicable to this system are described and evaluated with reference to these characteristics. Also included in this chapter are approaches for producing a satisfactory source which have not met with success. These are included to acquaint the reader with the pitfalls of these methods.

3.2 Requirements of the Point Source of Light

3.2.1 In order to qualify for point light source projection, a source must meet the following requirements:

(a.) The source must have a very small diameter. The smaller the source diameter the better the image definition possible and the finer the detail which can be projected successfully. A source with a diameter of .029" (Zirconium 25 watt) was used in the development of Device 2-FH-2. In cooperation with the de Florez study program, (2-FH-4), the Sylvania Company produced a concentrated arc lamp with a diameter of .013" (Hafnium). This lamp was subsequently used on Device 2-FH-2 and produced the same light output as the Zirconium source. Further work by the de Florez Company produced light sources with diameters as small as .0035" having greater light output than their predecessors.

(b.) A source must have a high luminance to provide adequate screen illumination of the projected display. Assuming that the radius, surface reflectivity of the screen and the transparency of the display-

object are established for a specific projection system, the brightness of the display-image is directly proportional to the light output of the point light source. This output in turn is dependent on two factors: (1) the intrinsic brightness or luminance of the point light source and (2) its diameter. Since the diameter of the light source is usually dictated by certain standards of definition required, it is apparent that the luminance of the source largely controls the display brightness.

(c.) Light coverage in azimuth and elevation should be adequate, preferably greater than the peripheral vision of the human eye. Then a single source can be used for the wide angle presentation.

(d.) The spectral distribution of the source in the visible range should include all wave lengths so that display-object colors are faithfully projected. Source color temperatures between 3000° and 6000°K appear to be satisfactory. Some adjustment of the light quality can be made by the use of suitable filters at the expense of light output. However, the color temperatures of the lamp can vary between wide ranges because of the characteristics of the eye. The eye can readily adjust itself to a gross color unbalance in the projected picture if the projection is in a completely darkened room. In this event the general adaptation level of the eye, both for color and brightness, is not influenced by room lighting and the effect is to make the projected colors appear more nearly correct than they actually are. However, if certain bands of color are completely absent from the spectral distribution, as with certain glowing vapor lamps, the projected colors can be noticeably distorted.

(e.) The envelope must be made as small as possible to permit bringing the source very close to the display-object, making possible high scale ratios and thereby increasing the operating range of the device.

(f.) The glass envelope surrounding the source should be free of striations which will project on to the screen and adversely affect the display-image. These striations can be particularly harmful since the projected images of the striations do not move along with the projected picture and therefore furnish the trainee with a cue that he is fixed in real space.

(g.) The heat radiation of the source should be low so that there is no danger to the display-object which can soften or burn under high temperature conditions. Dark areas within the transparencies, which absorb the major portion of heat energy, can be irreparably damaged. The introduction of a heat absorbing glass, which is externally cooled, considerably relieves this condition; however, the glass may interfere with the source approaching the display-object to within close limits. In addition, cooling certain lamps will adversely affect their performance.

(h.) The operation of the source should not expose personnel to danger. Certain super high pressure lamps explode after aging sufficiently, and if proper precautions are not employed, serious accidents may result. In addition, high energy lamps emit large quantities of ultra-violet radiation which is harmful to both skin and eyes in extreme cases.

(i.) On an average, the source should have a long life to minimize maintenance. Most lamps decrease in light intensity as the lamp ages. This is true of both the concentrated arc lamps and gaseous discharge lamps. Aging effects can be overcome to some extent. With the concentrated arc lamps this is done by increasing the current through the lamps. A super pressure lamp is best discarded for safety reasons if there is an appreciable loss in light intensity due to aging.

(j.) The point light source should be of reasonable cost.

3.3 Types of Point Source Lamps

<u>3.3.1</u> There are many types of light emitting sources that exist today and which are commercially available. Only a few of these lamps have the necessary prerequisites to be considered for use in a point source projection system. Only small diameter sources of high photometric brightness will be described in the following paragraphs. These lamps fall into two classifications:

(a.) Low pressure lamps which depend on a glowing metallic substance for light radiation.

(b.) High pressure lamps which depend on a glowing vapor for light radiation.

The former category encompasses tungsten filament lamps and Sylvania concentrated arc lamps. The latter category includes mercury and xenon arc lamps.

<u>3.3.2</u> Tungsten lamps were used successfully in Device 2-FH-2 as the side lights to supplement the projection of the zirconium concentrated arc lamp, which is only satisfactory for 150° of light coverage. Tungsten lamps can be made to operate close to the melting point of tungsten (3650°K), but relatively speaking, the lamps are of low photometric brightness (7000-8000 candles per square inch) and in order to obtain sufficient light output, the source diameter must be fairly large. Where definition can be compromised these lamps are sometimes adequate. They are particuarly useful because of the small envelope which encloses the source.

<u>3.3.3</u> A much more efficient light source is the Sylvania zirconium concentrated arc lamp which is made in the following wattage ratings: 2, 10, 25, 40, 100, and 300. These lamps operate at a temperature which is close to the boiling point of zirconium in a partial vacuum. The boiling point of zirconium at one atmosphere is approximately 5300°K. The brightness of these lamps is several times that of the tungsten family and is in the order of 23,000 candles per square inch. The increased brightness is obtained because of the high operating temperature. The brightness increase follows the Stefan-Boltzmann law which states that the total emissive power of a body is proportional to the fourth power of its absolute temperature.

<u>3.3.4</u> Basically, the concentrated arc lamp is an arc lamp provided with permanent metallic anodes and a special refractory cathode. These two elements are sealed within a glass bulb in a partial vacuum of argon, an inert gas. When the arc is established between the two elements

the cathode is raised to a temperature beyond the melting point.

3.3.5 Early in the component study program The de Florez Company interested the Sylvania Corp. in making a superior light source with a Hafnium cathode. This cathode replaced the Zirconium cathode in the standard 10 watt lamp. The Hafnium lamp, having a considerably higher boiling temperature than the Zirconium, can be operated at higher input power to emit substantially more light. These Hafnium lamps, when used in lieu of the Zirconium lamps in 2-FH-2, gave considerably better definition, especially noticeable in the "on-ground" position.

3.3.6 The source diameter, light output, and brightness of the Hafnium lamp varies with the power input to the lamp as shown in Figure 3-1. The diameter is.013" at 25 watts input. For this diameter the measured light output is approximately 13 candles and the calculated brightness is 80,000 cd. per square inch. This value is almost 4 times that of the Zirconium brightness and for this reason it is possible to obtain comparable light outputs for about one-half the Zirconium diameter (.029"). The color temperature of the Hafnium lamp is about 3300 °K and the light distribution is approximately that of the Lambert's Law emitter. The measured light distribution is shown in Figure 3-2. The lamp envelope permits the source to approach the display-object to within 5/16". The lamp can be externally cooled without affecting its operation so that it can touch the display-object without harmful effects. One minor undesirable feature about the lamp is the slight source "wander" within the refractory material. This condition, which is more of a minor distraction than anything of consequence, can be relieved by increasing the lamp current.

3.3.7 Throughout the study, source diameters were measured by either a micrometer microscope or by optical projection methods. The latter method involves projecting the source image on to a screen to make direct measurements of the enlarged image and then determining the magnification ratio of the optical system so that the actual source diameter can easily be calculated.

3.3.8 Variations in source diameter with current changes in this lamp can be used to advantage. It is possible to reduce the diameter when this lamp approaches the display-object to obtain better definition. The reduction in light intensity will probably not be objectionable because the images are enlarged and will therefore convey more information in spite of the lower brightness. In addition, the eye will not easily notice gradual changes in screen illumination because of its relative insensitivity to such changes.

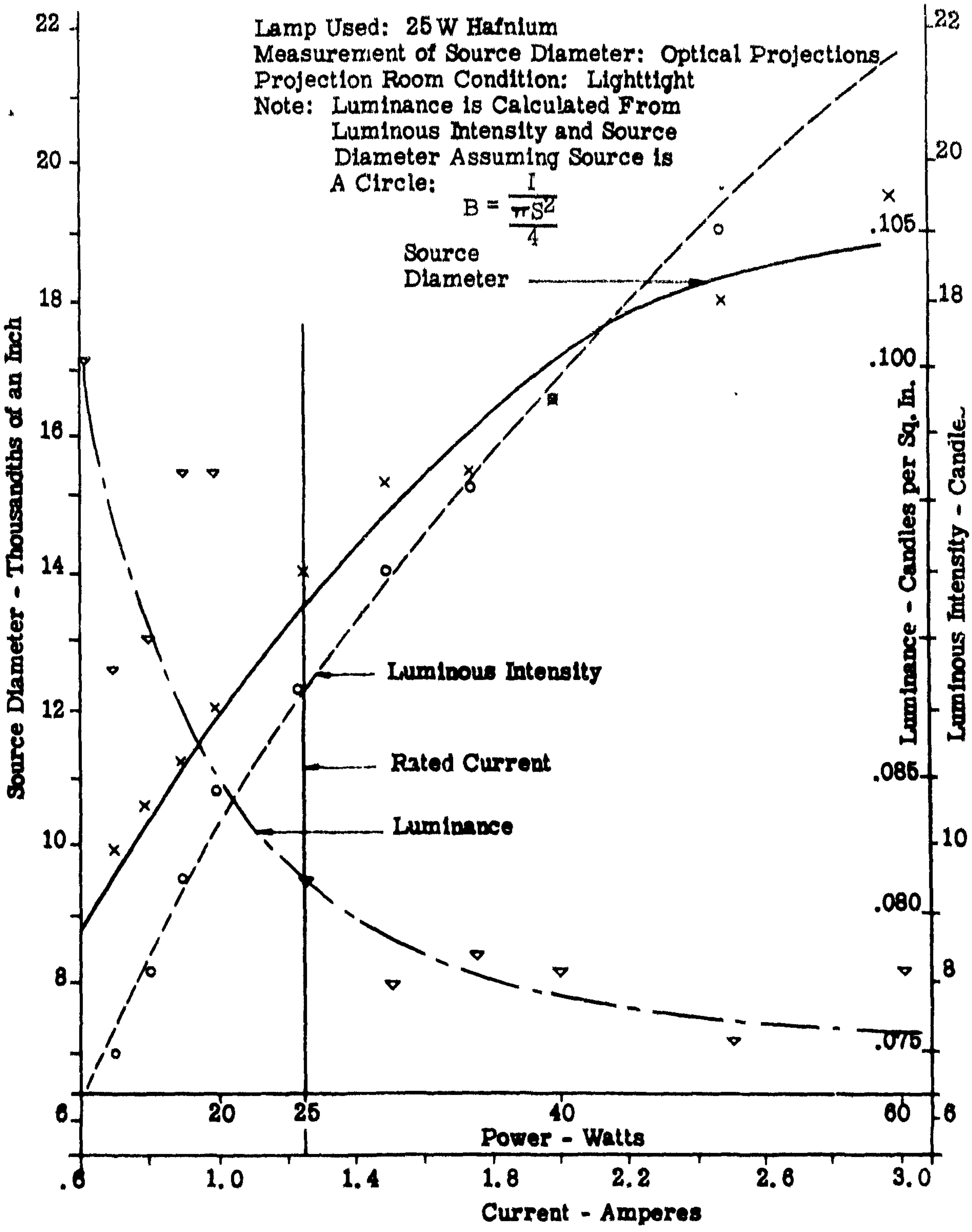


Figure 3 - 1 - Variations in Diameter, Luminous Intensity and Luminance With Changes in Current for a 25 Watt Hafnium Lamp.

LAMP USED: 25 W Hafnium - 1.3 amps (Source Diameter - .0135")

APPARATUS: Weston Lightmeter No. 1246
PROJECTION ROOM CONDITION: Light tight
DISTANCE BETWEEN LAMP & PHOTO CELL: 12"

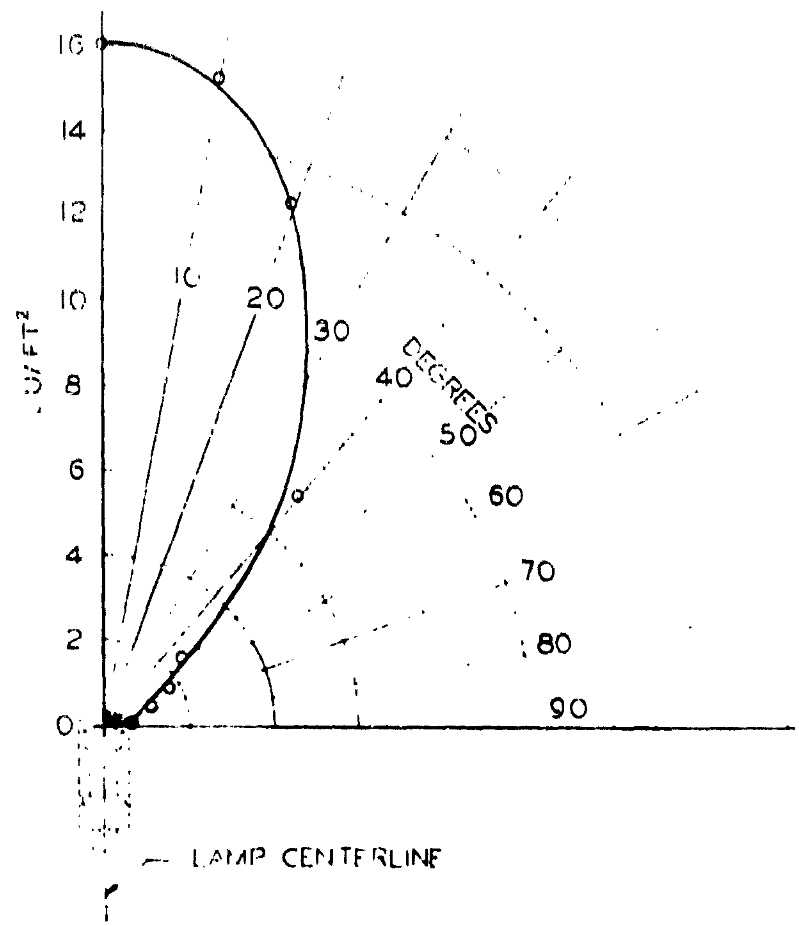


Figure 3-2 - Light Distribution of the 25 Watt Hafnium Lamp.

3.3.9 Several attempts have been made to interest Sylvania in making a hafnium lamp with a smaller envelope so that the numerical scale can be increased for some applications. To date these attempts have not been successful. Sylvania believes that to do this it will be necessary to reduce the anode area and as a result the lamp may operate at excessive temperatures. Moving the source closer to the envelope will have the further harmful effect of causing the hafnium vapor to condense on the glass surface, which will substantially reduce the light output of the lamp, and will cause the glass to absorb more radiant heat. All of these factors would probably result in an extremely short life for the lamp. It will also be necessary to use a harder and more durable glass envelope which presents additional problems. Sylvania has indicated, however, that it may be interested in undertaking this problem at some future time.

3.3.10 Sylvania has also been approached on the possibility of placing more than one cathode within the glass envelope with suitable light shields so that increased light coverage can be obtained. This, they feel, can be done but it will be necessary to increase the anode size to obtain sufficient cooling and as a result the envelope will necessarily be increased.

3.3.11 The HBO-109 Osram mercury arc lamp is a gaseous discharge lamp wherein an electrical discharge causes the mercury to glow. This process takes place at a high vapor pressure ranging from 35-70 atmospheres. Because of these pressures an extremely high photometric brightness is obtained rivaling the brightness of the sun. The radiation from this lamp is characteristic of the mercury spectrum but also has a faint continuous background of the incandescent electrodes. The chief lines in this spectrum of the mercury arc are as follows:

405 millimicrons (violet)
436 millimicrons (violet)
546 millimicrons (green)
577-579 millimicrons (yellow-gr[illegible]

Since the radiation in the visible range consists [illegible]marily of well defined lines, a color temperature cannot be assigned t[illegible] this lamp.

3.3.12 The only red radiation derived from this lamp is from the incandescent electrodes. The predominant violet radiation and lack of red causes the red areas in display-objects to appear wine colored. A substantial quantity of ultraviolet light is also radiated, which can be detrimental because it often causes crazing to occur in acrylic plastics due to a photochemical process. It will also affect the dyes in the display-object which are generally of an unstable nature under the best conditions.

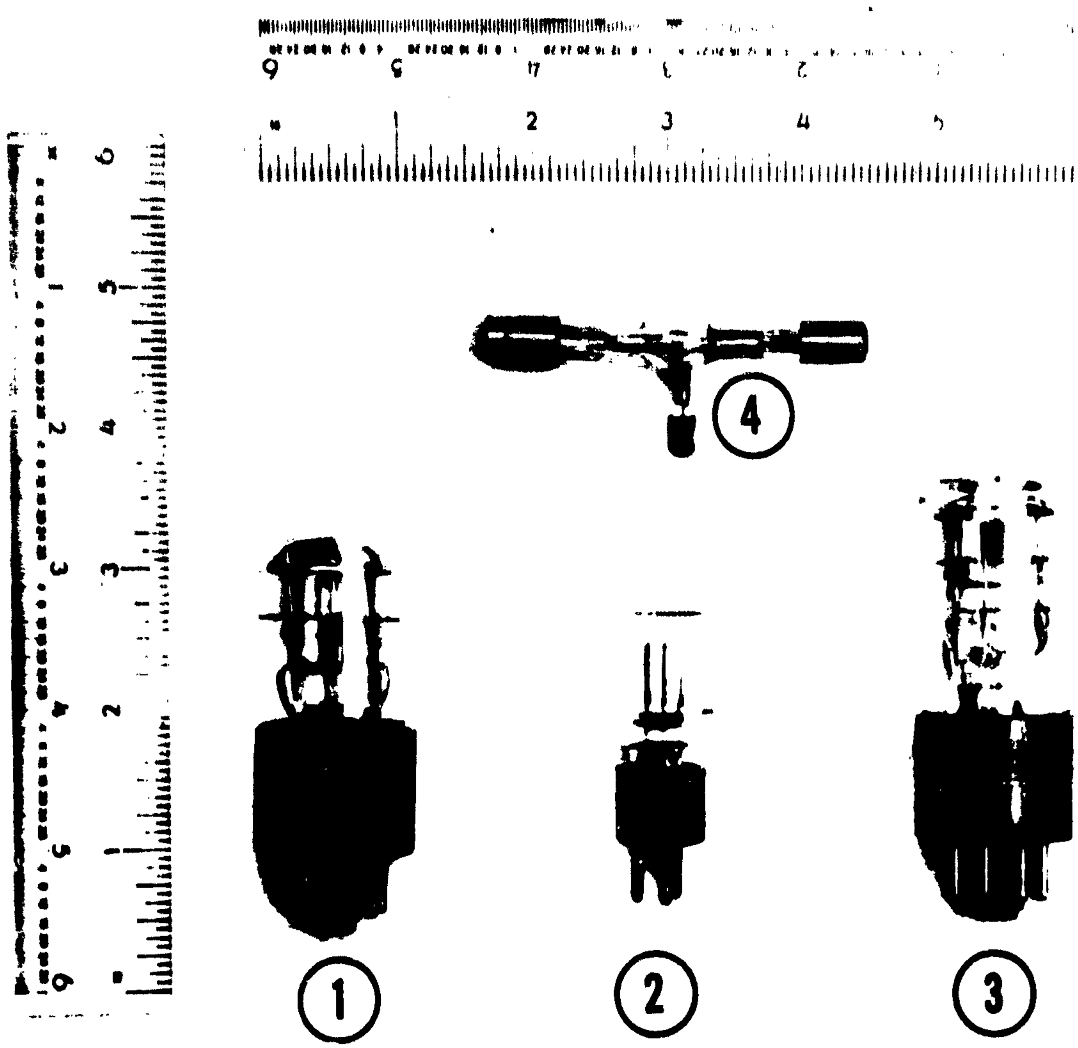
3.3.13 Figure 3-3 illustrates the physical characteristics of the lamp. The operating electrodes, which are 180° apart, are enclosed in a 1/2" diameter spherical quartz bulb. The electrode at right angles to the operating electrodes is used exclusively for starting purposes in the HBO-107 lamp. However, Osram now manufactures a mercury arc lamp without the starting electrode, the HBO-109.

3.3.14 When operated at its rating of 100 watts, the source diameter is .014" and emits approximately 250 candles. The photometric brightness is approximately 1 1/2 million candles per square inch. This is about 18 times that of the Hafnium lamp.

3.3.15 Variations in source diameter, light output and brightness with changes in power input for this lamp are plotted in Figure 3-4. It is important to note that as the power is reduced the source diameter actually increases and the brightness decreases. This is a result of the reduced pressures within the lamp which accompany the reduced power inputs. The effect of increased diameter is the reverse of that found in the Hafnium lamp, where reduced power input resulted in decreased source diameter. The curve of light distribution is shown in Figure 3-5.

3.3.16 Unfortunately, the Osram lamp emits a great deal of heat energy. For this reason it is difficult to use it directly as the projection source, particularly when the lamp must be operated very close to the display-object. Cooling the lamp, as is done with the Hafnium and Zirconium lamps is not advisable because of the resulting increase in source diameter and reduction in light output. Another disadvantage of this lamp is the high pressure which creates a safety problem to personnel. Fortunately, in spite of continued use, de Florez personnel have not experienced any ill effects from this lamp, except for an occasional "sunburn". This problem can be solved satisfactorily with ultraviolet absorbing filters or Plexiglas to make the transparency. A fact worthy of mention at this point is that fingerprints must be removed with alcohol and distilled water from the lamp before starting, so that the salts from oily fingerprints will not combine with and soften the quartz at high operating temperatures which will promote shattering the lamp envelope.

3.3.17 Without question, this lamp produces the brightest source of any lamp tested to date. It has particular value in that the source can be "de-magnified" further even at the expense of considerable light loss. This lamp has made it possible to use some of the optical approaches, which will be described in the following paragraphs, for obtaining even smaller source diameters.



Scales shown are in inches

Key
1. Sylvania 25 Watt Zirconium Arc Lamp
2. Sylvania 2 Watt Zirconium Arc Lamp
3. Sylvania 25 Watt Hafnium Arc Lamp
4. Osram 100 Watt Mercury Vapor Lamp-HBO-107

Figure 3-3 Assorted Point Source Lamps

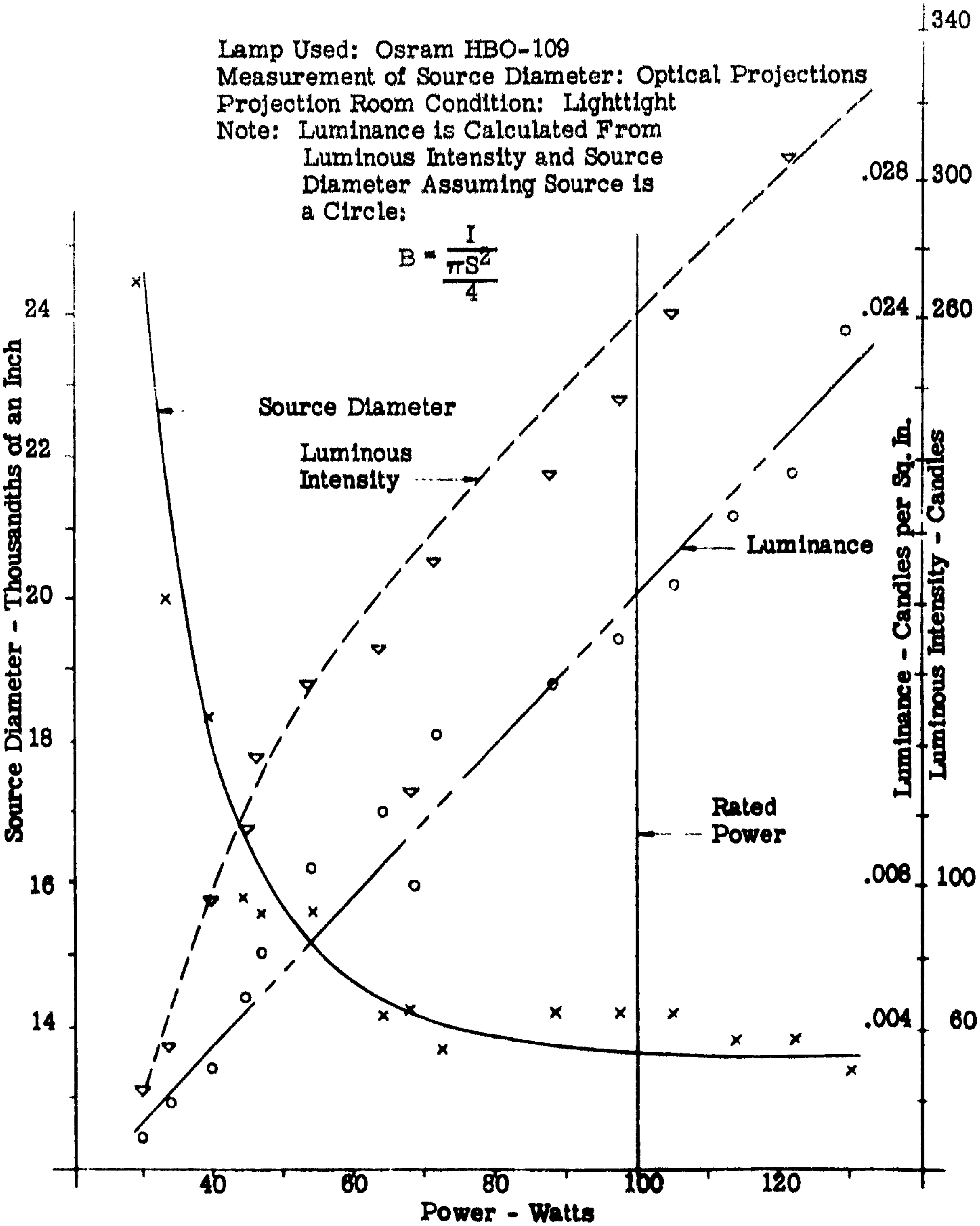


Figure 3-4 - Variations in Diameter, Luminous Intensity and Luminance With Changes in Power for Osram HBO-109 Lamp

LAMP USED: Osram HBO - 107 or Osram HBO - 109
APPARATUS: Weston lightmeter No. 1246
PROJECTION ROOM CONDITION: Light tight
DISTANCE BETWEEN LAMP & PHOTO CELL: 12"

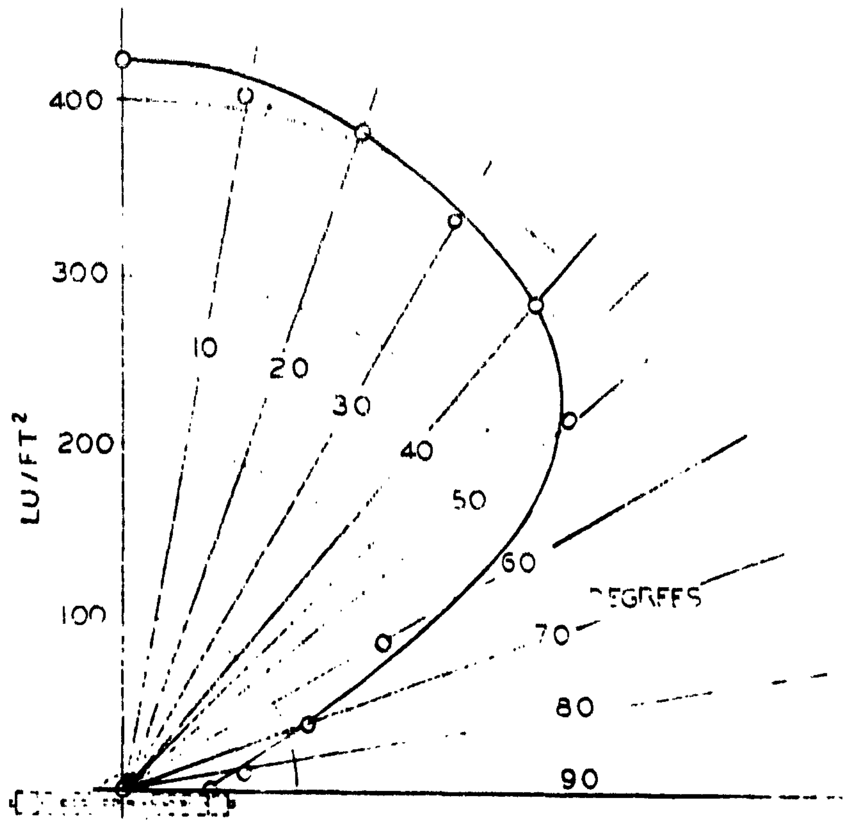


Figure 3 - 5 - Light Distribution of the Osram HBO-109 Lamp.

3.3.18 Representative point source lamps are shown in Figure 3-3. Appendix IV contains a list and pertinent data of the more promising point source lamps whose source diameters measure less than .100".

3.4 Reduction of Source Diameter by Optical Means

3.4.1 The method which has thus far produced the most satisfactory source for point source projection makes use of an optical system to reduce, or "demagnify", a real source such as the Osram point light source. The extent of reduction, the type of image which is formed (real or virtual), and the position of the source image is dependent on the character of and over-all focal length of the optical system, and the placement of the real source with respect to this system. The intensity, or light output of the source, is dependent on the luminance of the real source, the reduction ratio of the system and the efficiency of the optical system. It should be noted that the luminance of the image source can never exceed, and in all probability will be less than the luminance of the real source. As an approximation of the maximum intensity that can be obtained with an optical system for the image of a real source, the luminance of the real source should be multiplied by the area of the image source. A proof of this is given in Appendix V. Values of light intensity versus source diameter for a typical system are shown in Figure 3-6.

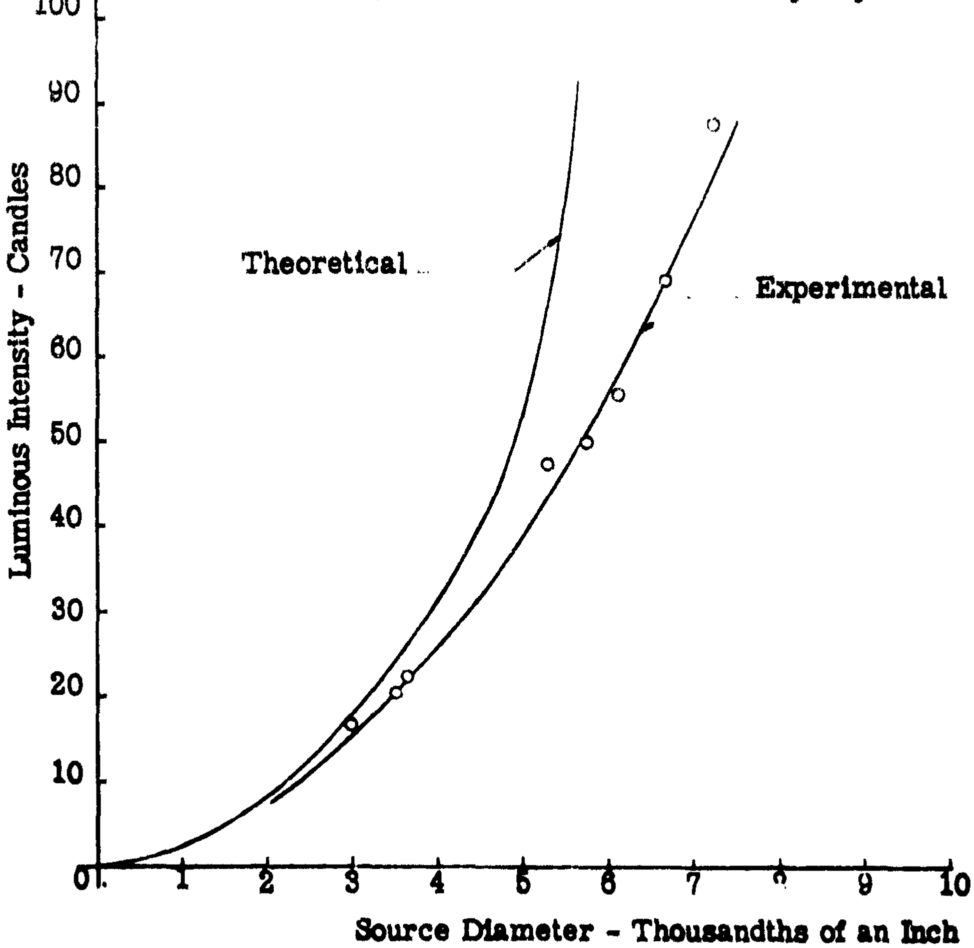
3.4.2 The light coverage which will be obtained with an image source depends on the numerical aperture of the optical system and the reduction ratio. In accordance with the Abbe sine law, the ratio of the sine of the exit half angle to the sine of the entrance half angle is directly proportional to the size reduction of the image.

3.4.3 Figure 3-7 schematically represents a typical optical system used to reduce a real source. It consists of a condenser lens or elements, an objective lens or elements, and a simple negative meniscus lens. The real source is placed at the focal point of the condenser system, thereby producing a collimated beam of light as the output. The collimated beam is converged by the objective lens to produce a real image of the source at the focal point of the objective. The reduction in size of the image is equal to the ratio of the focal length of the objective to that of the condenser.

3.4.4 The negative meniscus lens has a two-fold purpose. Its focal length and position are selected to obtain an additional reduction in the size of the image and to further disperse the light. Since the lens is negative, the image formed will be virtual and will appear to an observer to

Experimental Conditions

Real Source: Osram HBO-109 Lamp (110 W) with Luminous Intensity of 500 Candles at Diameter .016 in.
Apparatus: Weston Light Meter #1246
Projection Room Conditions: Lighttight



Theoretical Relationship from the Inverse Square Law

$$\frac{I}{S_1^2} = \frac{I'}{S^2}$$

where I = 500 candles and S_1 = .016 inches

Figure 3-6 - The Effect of Source Diameter on Luminous Intensity When Source Diameter is Reduced By Optical Elements

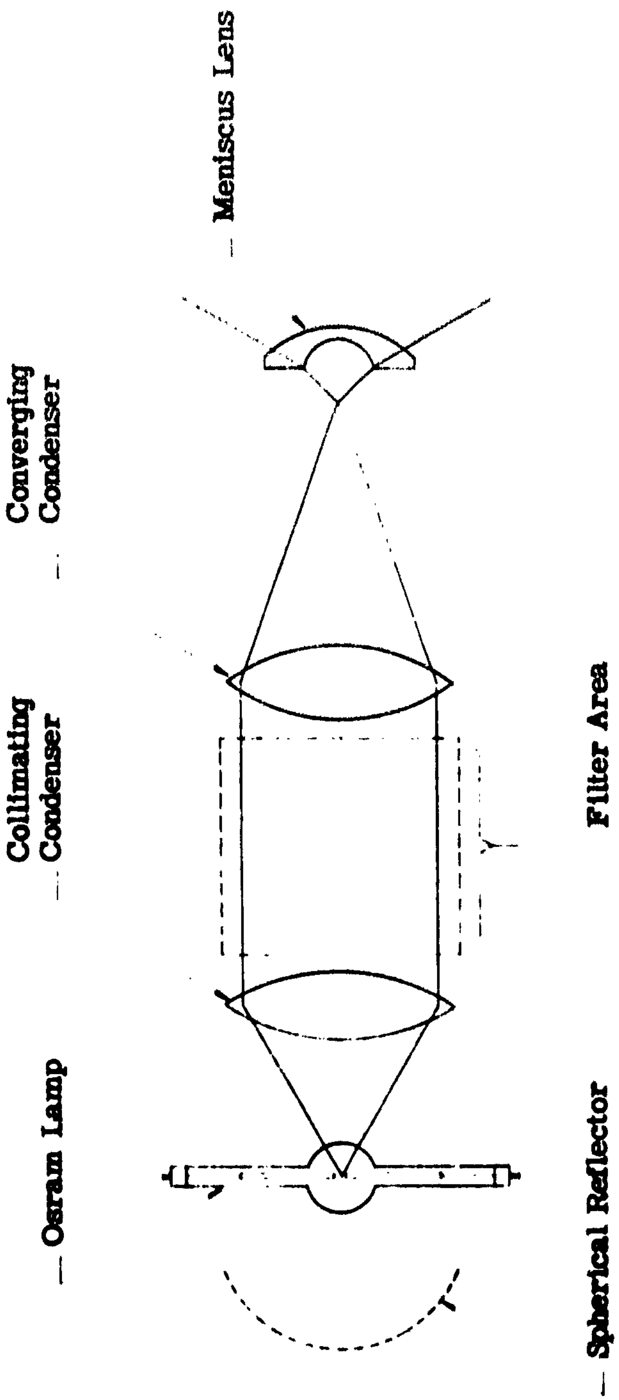


Figure 3-7 - Schematic Diagram of Optical Arrangement of de Florez Point Light Source, Model III.

be eminating from a point behind the meniscus lens. Appendix V fully explains the theory and application of the meniscus lens for demagnification purposes.

3.4.5 Utilizing an optical system typical of the one described, the de Florez Company has successfully produced light sources as small as .0035" having an intensity of approximately 18 candles along the optical axis. Light coverage is in excess of a complete hemisphere, although light output falls off sharply at the extremities of the hemisphere. Output in a particular direction varies directly as the cosine of the angle from the optical axis to the direction in question. This source can approach the display-object within .072 inches.

3.4.6 Any high numerical aperture condenser lens can be utilized in the optical system. However, the de Florez Company has been very successful through the use of a single element quartz condenser lens, since this lens must be placed in close proximity to the Osram lamp and be capable of withstanding the intense heat. To date spherical condensers have been used, although tests are now in progress utilizing two elements, one with parabolic surfaces, to eliminate the abberations accompanying spherical surfaces.

3.4.7 High numerical aperture microscope objectives have been used successfully as objective lenses. These are generally high quality lenses containing fewer light absorbing elements than photographic objectives, since their field is not extensive. All glass to air surfaces are usually coated in the objective to increase the optical efficiency of the system and to eliminate the possibility of ghost images due to reflections among elements.

3.4.8 Attempts have been made to increase the optical efficiency by placing a spherical mirror behind the Osram source, but it has been found that the source itself is fairly dense to the light rays which are returned and focused at the source. Consequently, efficiency is increased only slightly. It is also essential that the mirror be aligned perfectly or the final image will be larger than desired. It is generally true that, in the use of a mirror, any substantial increase in light output of the final image results from a misaligned mirror and an oversized image.

3.4.9 It is obviously important to use good quality lenses throughout the optical system since any abberations resulting from inferior lenses or design usually leads to an oversized image without an accompanying increase in light. Most good quality microscope objectives are sufficiently

suitable for the purpose since the only concern of the optical system is to form an image of a single point. Obviously, as it becomes desirable to reduce the diameter of the image further, aberrations become a greater concern.

3.4.10 A convenient location for the placement of filters to absorb heat, for color compensation, or for special effects, is that following the condenser lens where the light is collimated. Special fog and haze effects can be obtained utilizing graduated filters in this section in conjunction with auxiliary projection lights.

3.4.11 In order to obtain better definition for an "on ground" condition it is possible to reduce the diameter of the source with accompanying reductions of apparent altitude. By varying the position of any of the elements in the optical system a change in the reduction ratio is achieved. However, there is an accompanying decrease in the angle of light output.

3.4.12 Figure 3-8 illustrates a typical assembled optical system and figure 3-9 shows typical optical elements.

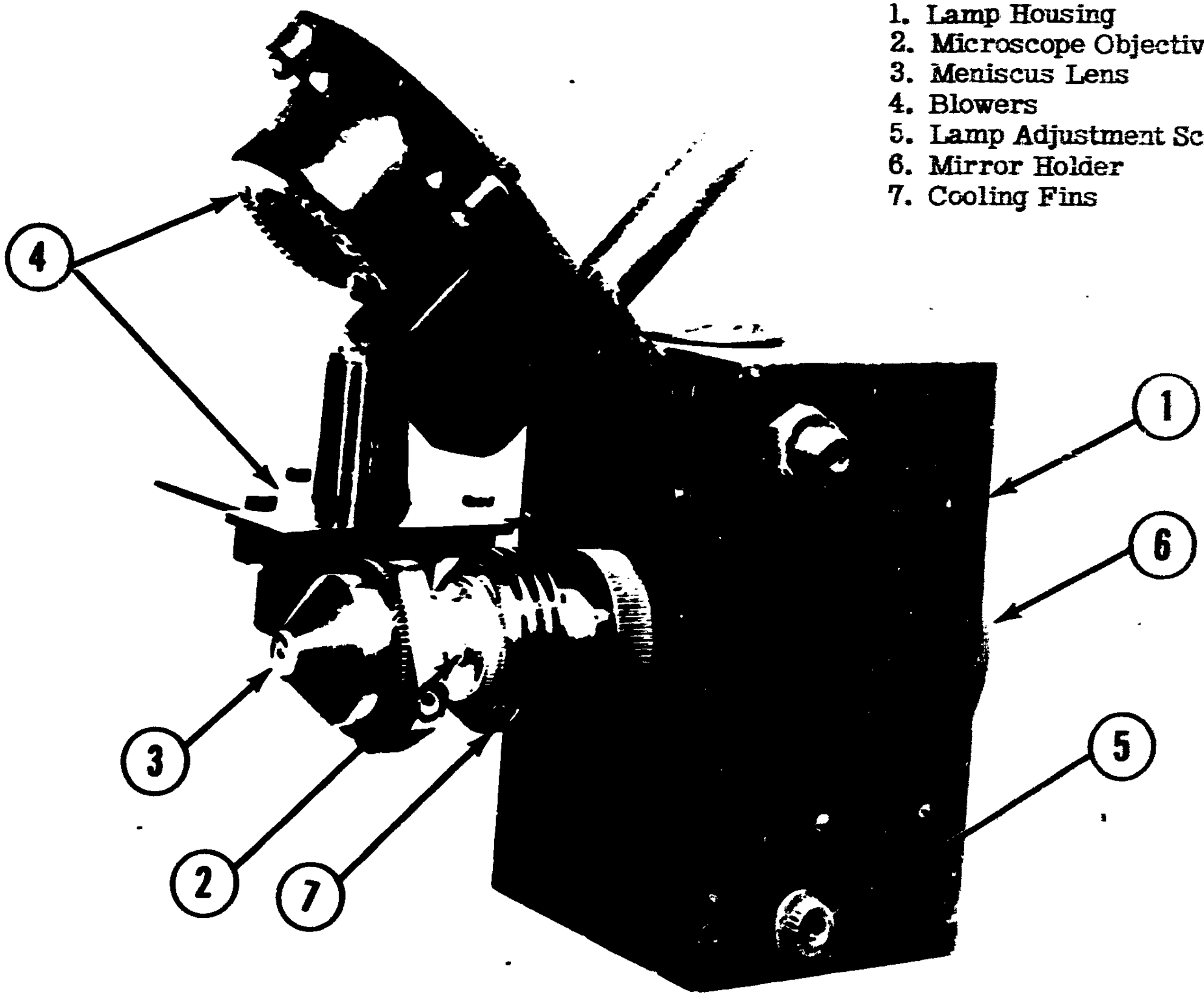
3.5 Other Approaches to Obtain a Small Source Diameter

3.5.1 During the course of the study made by the de Florez Company several unsuccessful attempts towards obtaining a small diameter source utilizing various approaches were made. These have been noted in the ensuing paragraphs and are presented primarily to discourage any further work along identical lines.

3.5.2 Producing Small Diameter Sources by "Piping" Light

3.5.3 An investigation was initiated early in the study phase of this project to determine the possibility of taking advantage of the characteristics of acrylic plastics to "pipe" light to produce a small diameter source. It was believed that a plexiglas cone could be used to concentrate the light by introducing a large quantity of light at the base of the cone, and after repeated internal reflections, the light would emerge from the point of the cone in concentrated form. This system makes use of the principle that if light in a dense medium strikes a surface of a rarer medium at an angle of incidence greater than the critical angle, the light is totally reflected. For plexiglas, with a refractive index of approximately 1.5, the critical angle is about 42°.

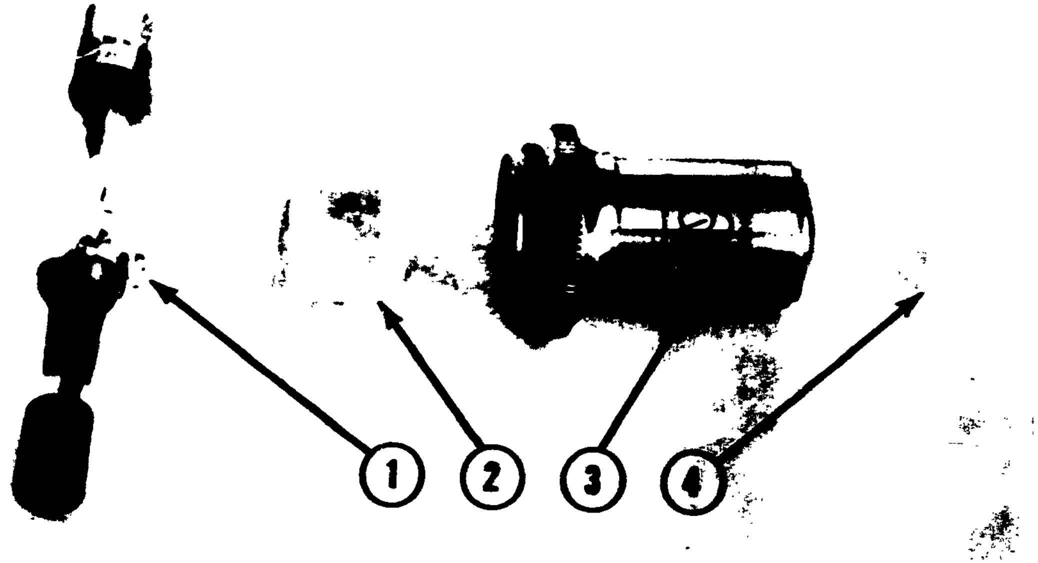
3.5.4 The system described appeared to have many advantages. The concentration of light at the tip could make it possible to approach the



<u>Key</u>

1. Lamp Housing
2. Microscope Objective
3. Meniscus Lens
4. Blowers
5. Lamp Adjustment Screw
6. Mirror Holder
7. Cooling Fins

Figure 3-8 De Florez Point Light Source, Model I



Key
1. Osram Lamp-HBO-109
2. Quartz Condenser
3. Microscope Objective
4. Meniscus Lens

Figure 3-9 Optical Elements

display-object very closely with the source. In addition, it is possible to separate the infra-red radiation from the visible light radiation conveniently by the use of suitable filters anywhere in the path of the light. Convecting air currents at high temperatures would pose no problem to the display-object, since the light source itself would be far removed from it. It was believed that a great quantity of light could be "funnelled" into the cone even at the expense of poor efficiency to obtain a bright source.

3.5.5 Figure 3-10 is a diagrammatic sketch of the test set up used to evaluate the principle. A ray of light, on striking the surface of the cone, is bent by an angle equal to the total cone angle after each reflection so it is easy to ascertain the maximum number of reflections possible before the angle of incidence is reduced to a value below the critical angle and the light ray is allowed to pass out of the cone after being refracted. The condenser system was used to concentrate the light at the tip so that more light would emerge from the tip by avoiding unnecessary reflections. Figure 3-11 is a photograph of the test model. Figure 3-12 is a photograph of the tip itself. Figure 3-13 illustrates the various shapes of tips tested.

3.5.6 The results of the tests made were not encouraging and this method was abandoned in favor of the meniscus lens system. The results can be described briefly as follows:

(a.) Light transmission efficiency dropped markedly as the diameter of the cone tip was reduced. Efficiencies of approximately 30% were obtainable for diameters of about 1/8" but were reduced to a few percent as the tip diameter was decreased below 1/32". Most of the light escaped from the plexiglas cone in the last 1/4", and while it was possible to recover a portion of this light by the addition of a reflecting aluminum foil cone around the tip, the total light output was low for small diameter sources. It was definitely established experimentally that very little of the light was absorbed by the plexiglas and that the greatest portion of light loss was a result of the repeated reflections within the cone. It should be noted that a light ray on striking the surface of the cone at angles greater than the critical angle is not totally reflected at an angle equal to the incident angle but a small percentage of the light is reflected back along the path of the original ray.

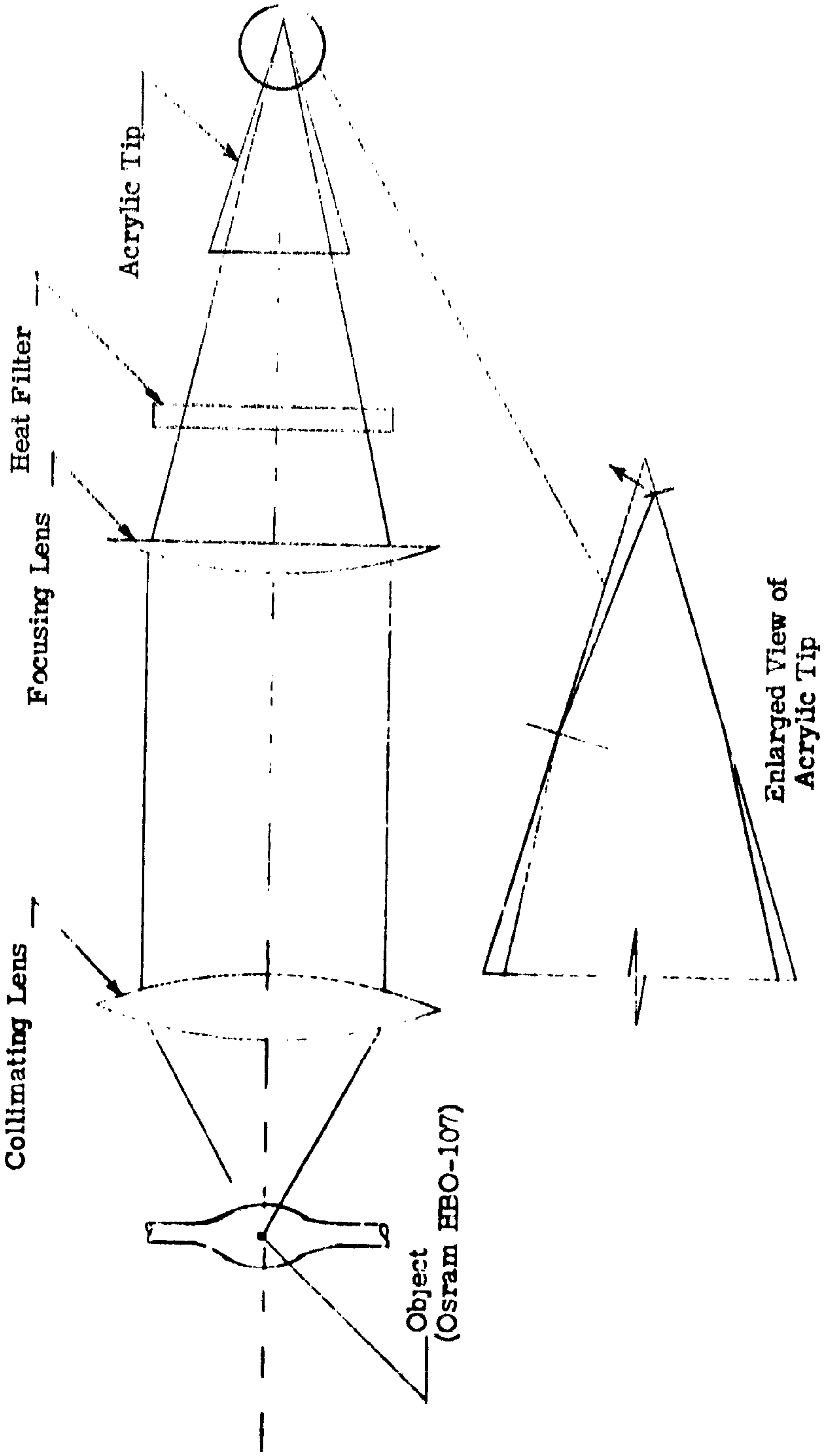


Fig. -10 - Schematic Diagram of Optical Arrangement for Formation of a Point Source by Use of an Acrylic Tip.

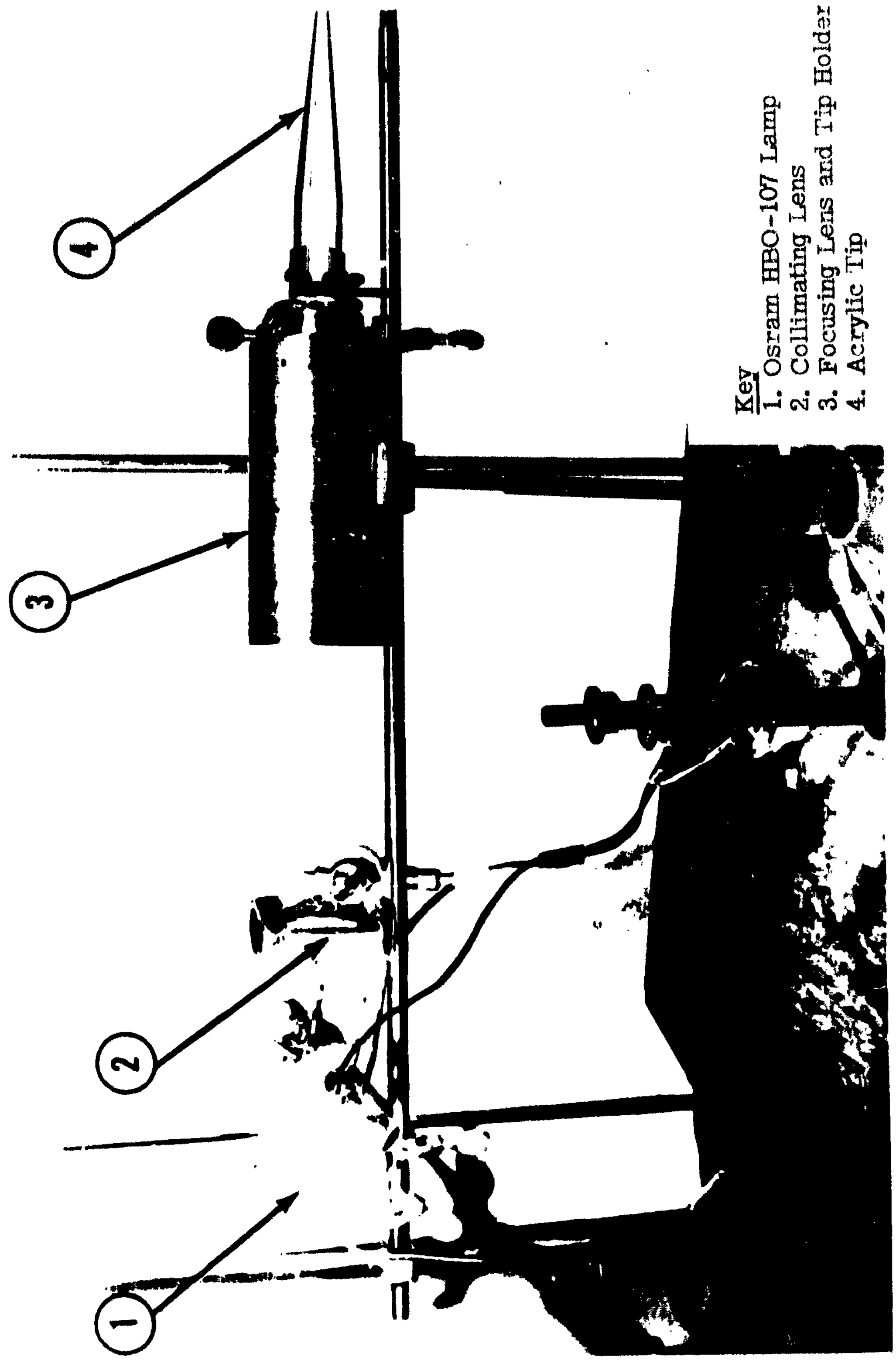


Figure 3-11 Experimental Equipment for Testing Light Concentrating Powers of Acrylic Tips

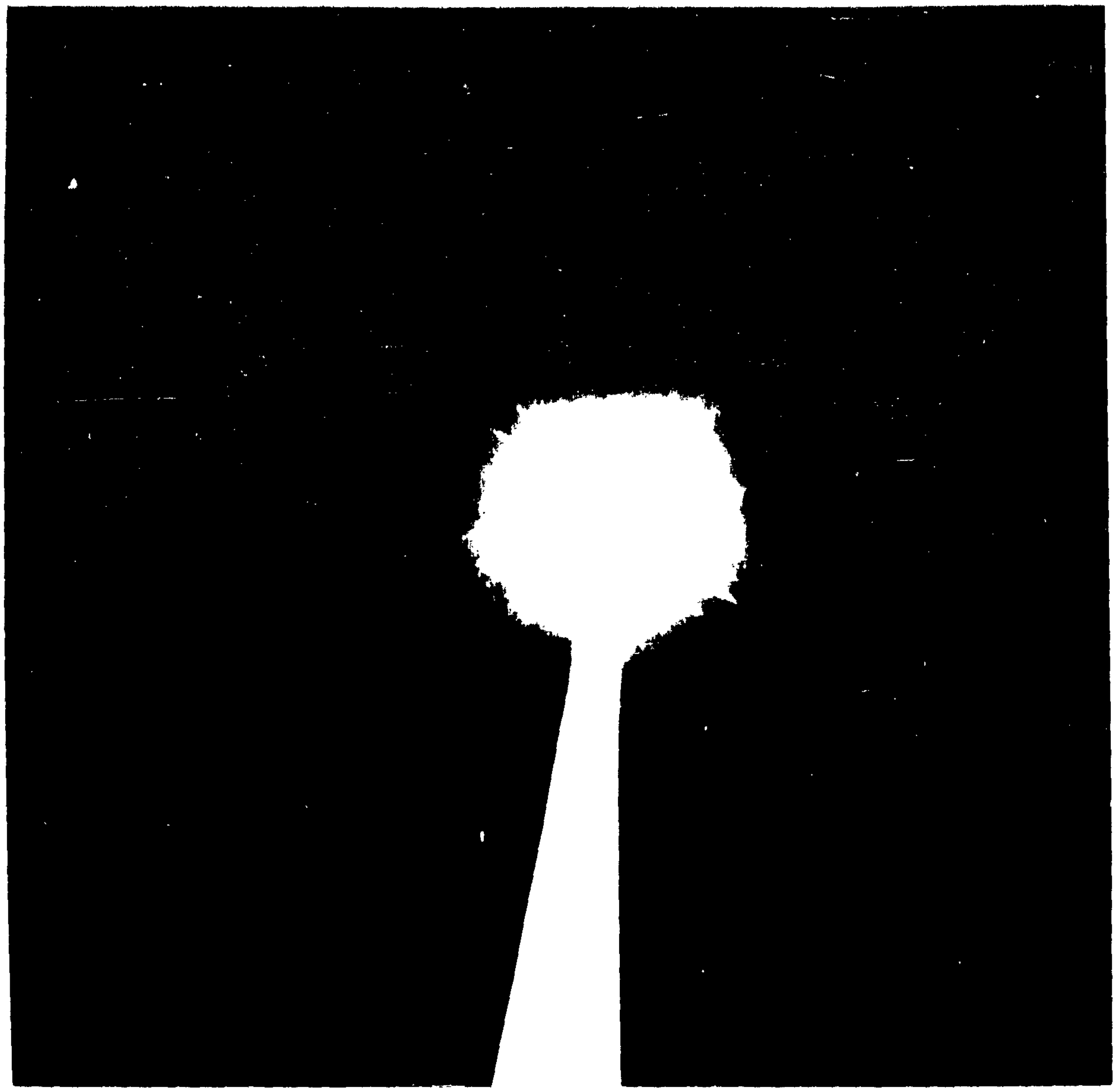


Figure 3-12 Light Concentration by an Acrylic Tip

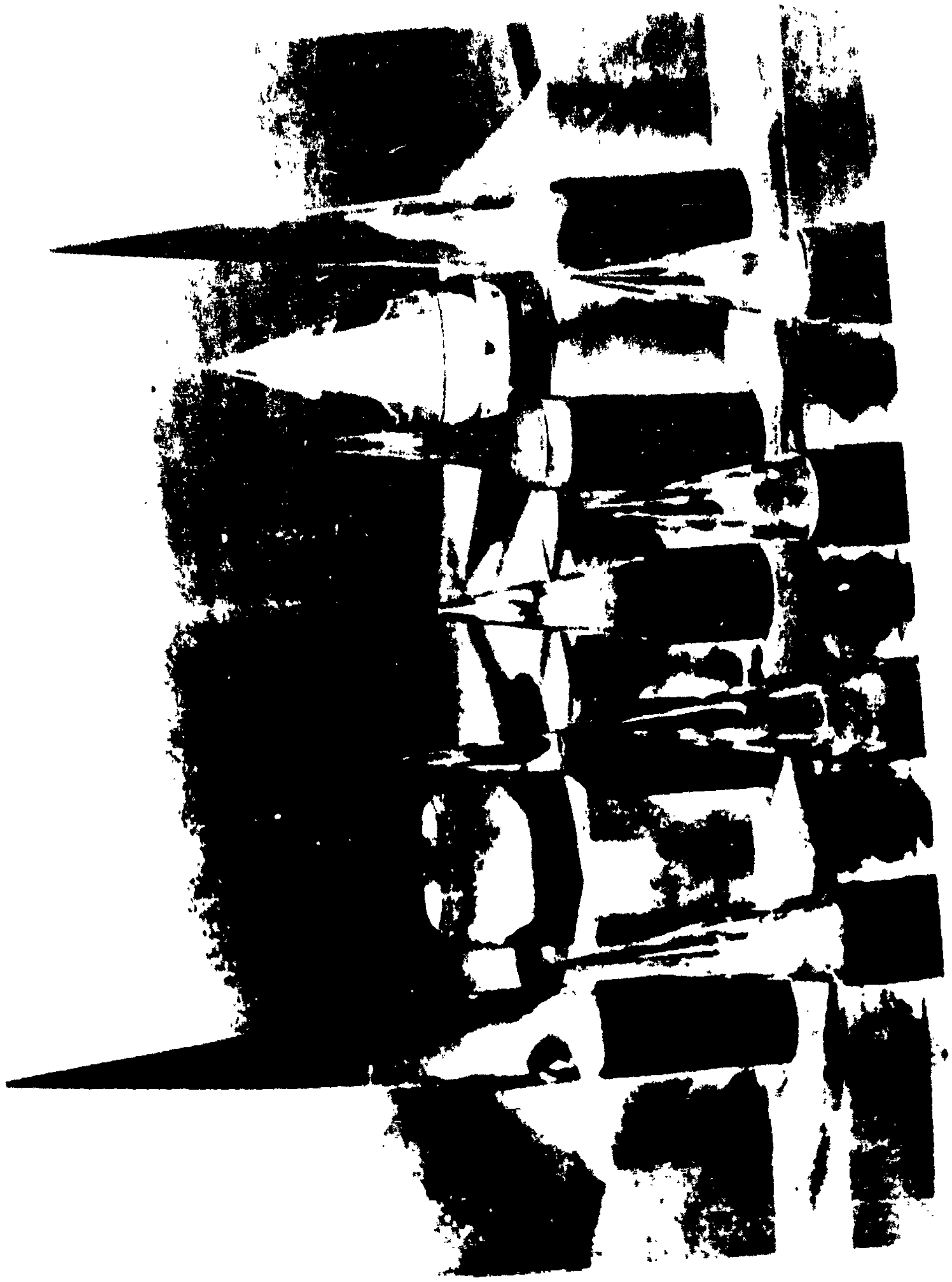


Figure 3-13 Assorted Acrylic Tips for Light Concentration Tests

(b.) It is not possible to obtain a light coverage beyond twice the critical angle of Plexiglas (total angle 84°) without employing other means for obtaining the uniform dispersion of light. One such method would be to roughen the Plexiglas tip; but this results in large light losses.

(c.) It is extremely difficult to obtain a uniform light distribution because the small tip does not permit an accurate control of the light emitting surface. The reader will appreciate the difficulty of obtaining a uniform dispersing surface of extremely small diameter.

(d.) Severe light dispersion, caused by the refraction of different wave lengths, resulted in many color patterns emitting from the tip.

3.5.7 The possibility of using a highly reflective aluminum cone to concentrate light in a similar fashion as the Plexiglas cone also was studied for a brief period of time. This work did not show any promise and the method was immediately discarded.

3.5.8 Additional Attempts at Obtaining an Improved Point Source.

3.5.9 Other approaches which were pursued to obtain an improved point source but which did not lead to significant results will be mentioned here. These approaches appear to be theoretically sound but have not been successful because of practical or manufacturing limitations:

(a.) The possibility of using a new material with a very high boiling point as the cathode in the concentrated arc lamps was discussed with Sylvania. Under consideration was the use of tantalum carbide, which Sylvania has used in the manufacture of some of its larger and more brilliant lamps. Sylvania attempted to make a lamp in the 25 watt size utilizing this material, but after several failures, abandoned the method. The tantalum carbide was extremely difficult to grind in very small diameters (about .015") because of the brittle nature of the material. In addition, when this problem was resolved, it was found that the impurities in the tantalum carbide were quickly vaporized when an arc was established

and consequently the cathodes immediately weakened and broke off.

(b.) The possibility of pressurizing the concentrated arc lamp was also discussed with Sylvania so that the boiling point of the cathode material could be substantially raised. Sylvania indicated that this would require more development work than was economically feasible due to the small demandfor concentrated arc lamps.

(c.) The possibility of reducing the distance between the electrodes of the Osram lamp was discussed with the manufacturer. The indication from Osram was that this was not practical to do because of the danger of shorting out the electrodes after expansion as a result of the operating temperatures.

(d.) The possibility of introducing a mechanical shield, with a small diameter hole, (.005" or less) within the envelope of the Osram lamp and very close to the source so that the hole would establish the source diameter was not considered practical. Osram did not feel they could properly support such a shield within the envelope. They also felt the arc would be shorted by the shield and that the high operating temperatures would pose a problem in locating a suitable shield material. The maximum theoretical coverage that could be obtained with a lamp of this kind would be 180° but in all probability the shield could not be placed close enough to approach this value.

(e.) The possibility of using mirrors to reduce the source diameter of the Osram lamp was discussed with individuals familiar with the design of optical mirrors. The indication received was that there is no easy and inexpensive method for obtaining this result and that optical lenses appeared to be a better approach.

CHAPTER 4

The Display-Object

4.1 Introduction

4.1.1 While, as previously mentioned, the display-object may be either transparent or reflective, the major portion of the work to date has been devoted to development of the former. A very considerable amount of this work in the 2-FH-2, 2-FH-4 and 2-FH-5 programs was devoted to development of suitable methods for producing satisfactory transparencies (a more convenient term for transparent display-object). Despite these efforts, this component still lags behind all others in the state of the art since it requires considerable expenditures of time, effort and money to produce a satisfactory transparency. This chapter deals primarily with the production of rigid and flexible transparencies, both hand decorated and photographic. It also describes several special transparency types, reflective display-objects, and the problems associated with the manufacture of each.

4.2 Requirements for a Satisfactory Transparent Display-Object

4.2.1 A good transparency should possess the following qualities:

(a.) The transparency should be reasonably realistic, having good detail and color contrast to contribute to the realism. The details should be sufficiently accurate to present genuine visual cues to the observer.

(b.) The transparency should be free of striations and imperfections which will detract from a realistic presentation.

(c.) The transparency should have good light transmission characteristics.

(d.) The transparency should have good physical characteristics, including the strength to support its own weight, good resistance to

tear, bending, and abrasion.

4.3 Types of Transparencies

4.3.1 Transparencies fall into two physical types: rigid and flexible. It is unfortunate that rigid transparencies are limited to the smaller sizes for they have considerable advantage over the flexible type. They are easier to manufacture. Dyeing this type presents few serious problems, due to the nature of the transparency and dye materials. In addition the base material is considerably clearer than the flexible type and there is less light absorption when compared to the flexible type. Generally speaking, a rigid transparency requires a less elaborate suspension system and usually there is no need to get involved with troublesome seams as with flexible types. The mounting of 3-D objects presents few difficulties. A good example of this type is shown in Figure 4-1. The base material for this transparency was Plexiglas II-A. This transparency was approximately 6' square and was utilized on device 2-FH-2.

4.3.2 The single advantage of flexible transparencies is the fact that a more compact mechanical system can be designed to support them since they can be readily rolled on to a drum, or they can be looped as many times as is necessary and treated as an endless belt. It is therefore possible to utilize a flexible transparency to simulate an extensive area. For example, a transparency for Device 2-FH-2, which was made of rigid Plexiglas, had an actual area of only 36 square feet. By comparison it is planned to use a flexible transparency for Device 2-FH-5, which contains over 450 square feet.

4.3.3 The materials most commonly used in the manufacture of flexible transparencies are acetates and duPont Cronar (a polyester base on which is placed a photographic emulsion). The base material for Cronar is identical to duPont Mylar, a very tough plastic possessing excellent strength and tear characteristics. In addition its optical clarity is as good as, or better than any other flexible plastic materials; however, it is not as good as some of the rigid plastic bases such as Plexiglas II-A.

4.3.4 During the course of the 2-FH-4 investigation many transparency bases were tested to determine their applicability to the point light source technique. Appendix VI lists only the more promising materials tested and gives the pertinent information on each material. Following this data is a list of materials tested, but which proved unsatisfactory on at least one of several accounts. Included in Appendix VI are both the rigid and the flexible types.

4.3.5 Figure 4-2 illustrates the use of a flexible transparency in combination with a pulley conveying system. In order to keep the trans-

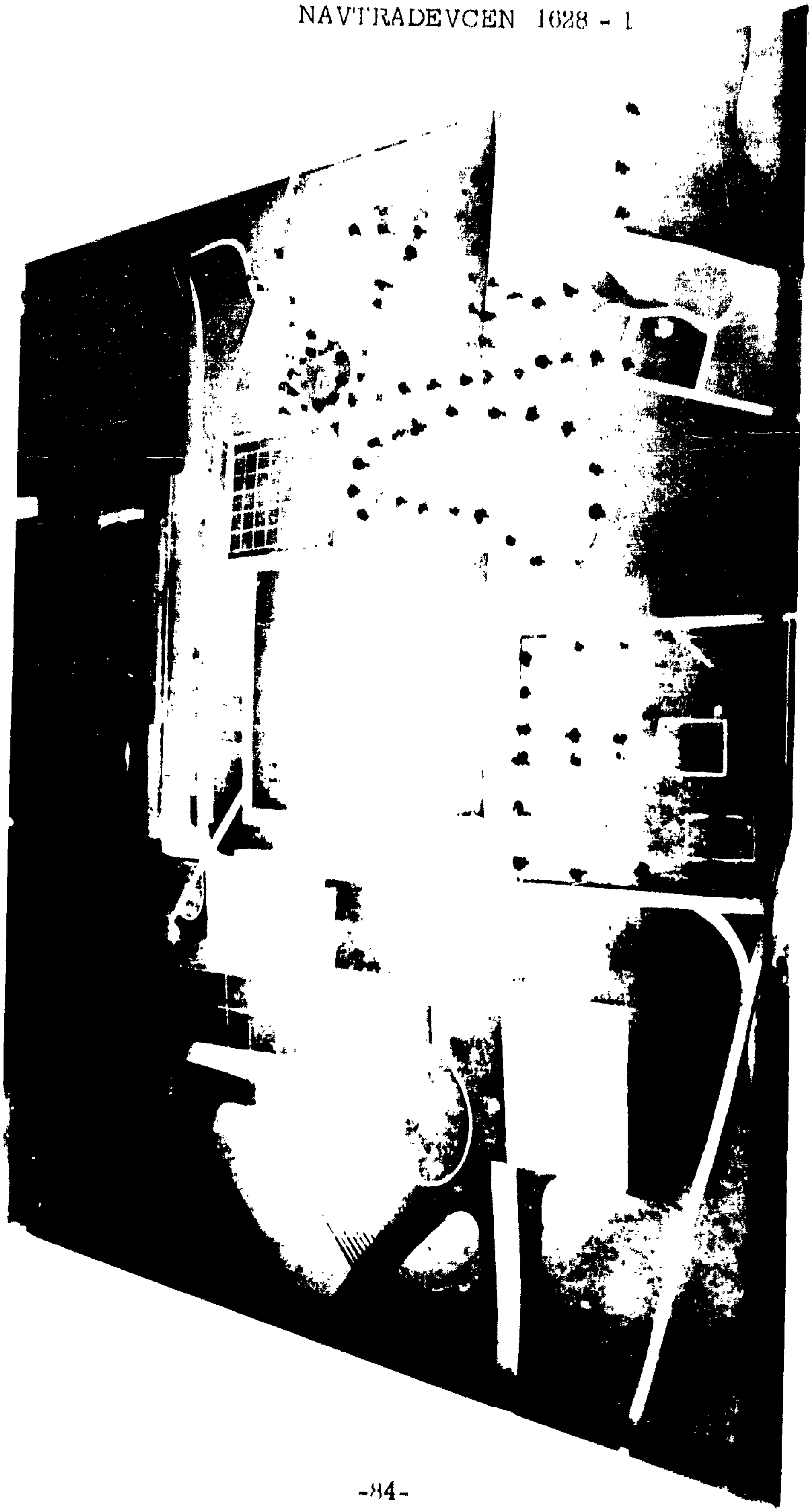


Figure 4-1 Example of a Rigid Transparency

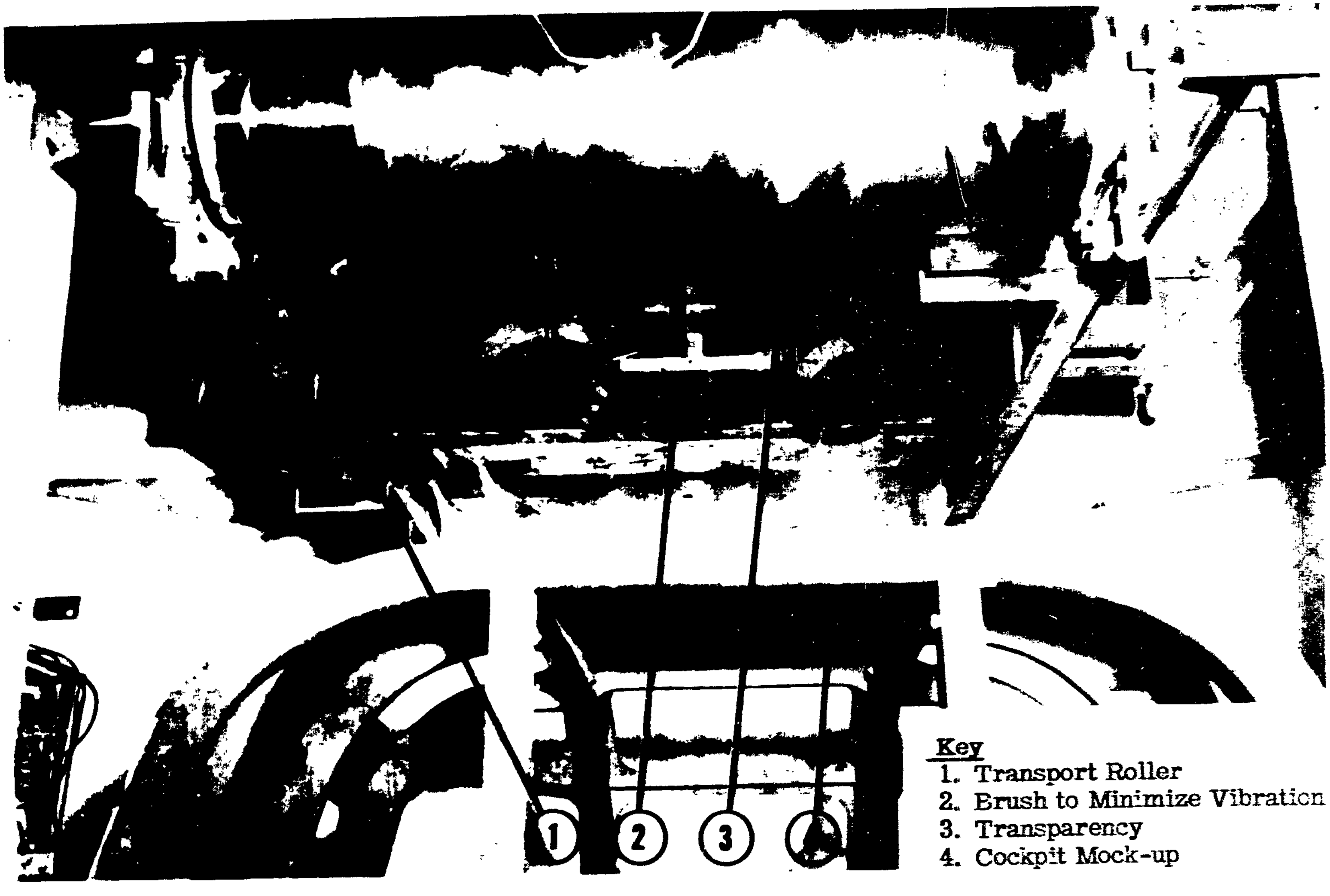


Figure 4-2 Illustration of a Flexible Transparency

parency perfectly flat and to reduce the amplitude of transparency vibrations, which are very troublesome in this type of display-object, the transparency is subjected to considerable tension (approaching 100 lbs per linear foot). For this reason Cronar has found considerable use, since its tensile strength is among the highest in plastics.

<u>4.3.6</u> To facilitate proper tracking of the flexible transparency on the conveyor pulleys, special self-aligning rollers, licensed by the U. S. Steel Corp. under the name of "Lorig Aligner Rollers", are contemplated for Device 2-FH-5. These rollers do not require any external control mechanism to achieve proper tracking, but equalize lateral forces in the transparency by self adjustment of the roller outside sections which are free to move.

<u>4.3.7</u> The use of Cronar has presented a few serious difficulties. This material cannot be seamed easily. It requires a special coated tape (.001" thick) to form a lap joint under the action of substantial heat and pressure in order to obtain transparencies which are wider than 42", the limiting width of Cronar. The special tape is manufactured by the G. T. Schjeldahl Company located in Northfield, Minnesota.

<u>4.3.8</u> Another problem, associated with flexible transparencies, is the mounting of 3-D objects. In order to allow for the passage of 3-D objects around a conveying pulley, the pulley must be grooved. This is shown in figure 4-3. The grooves necessitate the programming of the 3-D objects to a considerable extent since they must appear within well-defined lines.

<u>4.3.9</u> It has been considered possible to off-set the advantage of the flexible material by using sheet-feeders and repilers to maintain the continuous flow of rigid transparencies. Another possibility for maintaining a continuous flow may be by making a continuous belt of rigid transparencies by hinging the various sections together and obtaining an action similar to a sliding overhead garage door. Obviously, either of these systems necessitates the use of a very complicated transparency conveying system.

<u>4.3.10</u> Generally speaking, rigid transparencies are more easily dyed by hand decorated techniques while the flexible type are usually manufactured by a combination of hand decorated and photographic techniques. Although the use of Mylar presents many great advantages, it possesses a few drawbacks. The material is impervious to practically all dyes and, consequently, a photographic emulsion, which can be dyed readily, must be used to manufacture the transparencies.

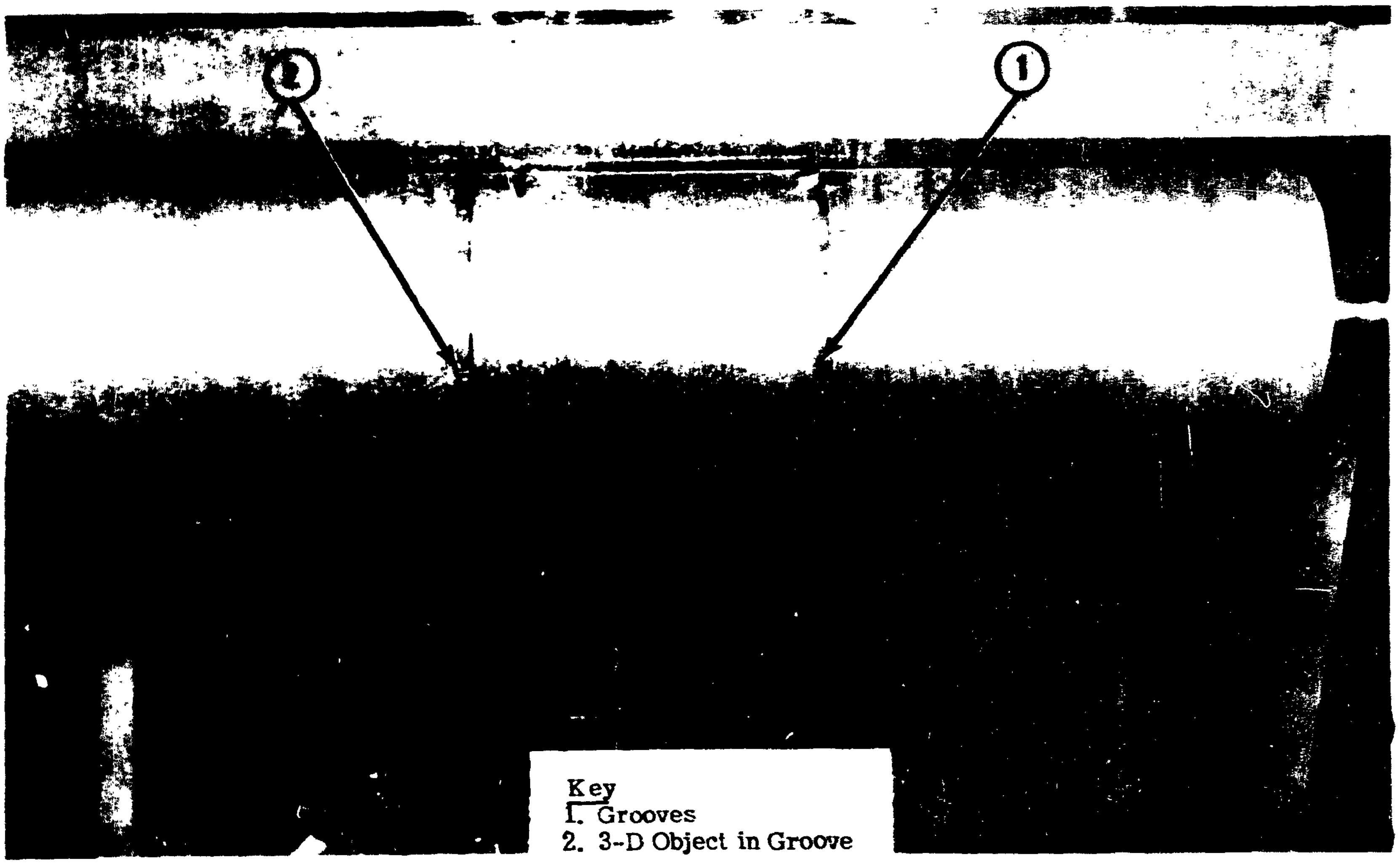


Figure 4-3 Clearance Grooves in Rollers for Three Dimensional Objects on a Transparency

4.4 Manufacturing Techniques

4.4.1 Manufacture of Transparencies by Hand Decorated Techniques.

4.4.2 Several types of dyes are available which are capable of dyeing Plexiglas either by the dip process or spraying. In addition, these dyes can be applied with brush or pen. Dip dyeing generally leads to the most satisfactory results insofar as light transmission is concerned. However, it is the most time consuming since it requires special clay barriers to be erected on the transparency, outlining the area to be dyed. This technique is especially troublesome on curved surfaces.

4.4.3 Color is generally applied to large areas by spraying. Color saturation is usually controlled by the proportion of inks and solvents in the spray solution. The dye solution should be sprayed by someone skilled in the art. Respraying a surface to obtain additional color density is not usually successful, and generally results in fogging the surface. This drastically reduces light transmission. If respraying a surface becomes necessary, the surface scum, which usually forms due to respraying, can be removed by applying wide masking tape to the dried, foggy surface and then removing the tape. This usually carries the surface deposit with it and will generally improve light transmission with some dyes.

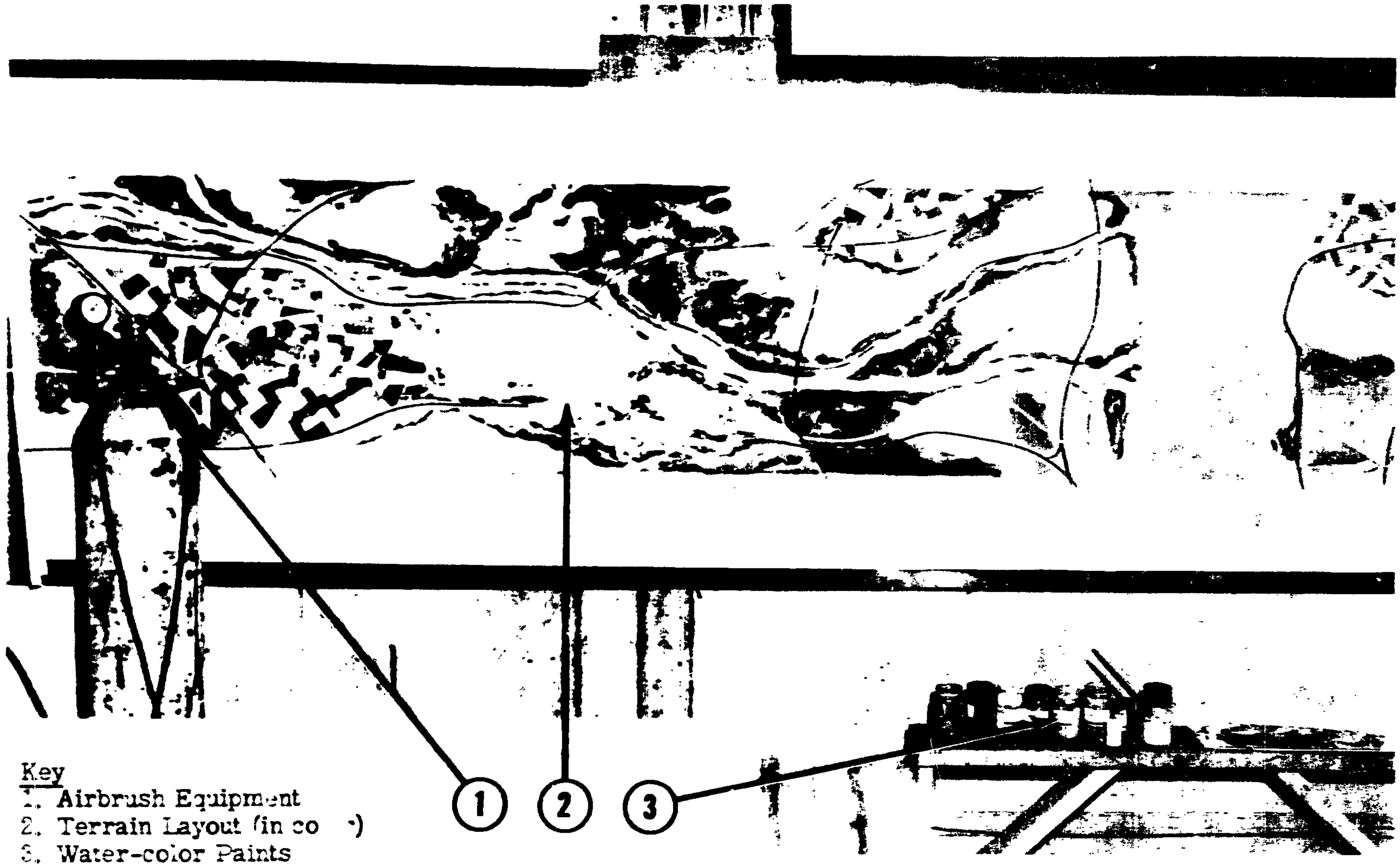
4.4.4 For very fine line work the rigid base materials can be etched with a scriber. Appendix VII is a listing of pertinent data for all of the materials which have been used to apply color to plastic materials. These dyes are rated according to the method of application.

4.4.5 The Manufacture of Hand Decorated Transparencies Utilizing Photographic Techniques

4.4.6 As explained previously, the photographic technique has wide application in the making of transparencies on Cronar since the photographic emulsion will easily receive art work, whereas, the base material will not. The various steps in the production of such a transparency are as follows:

(a.) Layout of the area to be depicted to a suitable scale. See Figure 4-4.

(b.) Sectionalizing the layout so that it can be reproduced to some other scale, namely the



Key
1. Airbrush Equipment
2. Terrain Layout (in co)
3. Water-color Paints

Figure 4-4 Original Layout of a Typical Area for a Transparency

scale selected for the final transparency, Figure 4-5.

(c.) Layout of the basic information to scale on Cronaflex utilizing guide lines to depict large areas. See Figure 4-6.

(d.) Masking the Cronaflex overlay prior to airbrushing as shown in Figure 4-7.

(e.) Actual airbrushing of the Cronaflex (original positive transparency) to obtain the effect of a continuous tone. Spraying is done with black inks. Figure 4-8 shows a completed airbrushed section.

(f.) Manufacture of a negative of the Cronaflex positive by photographic techniques. This negative can be retouched prior to printing the Cronar positive if corrections are required for any reason. Exposure of both negative and positives can be done in a vacuum frame in sections or with a continuous printer. With the former technique extreme care must be exercised to obtain proper registration between the sections.

(g.) Combining the various sections of the transparency by seaming them.

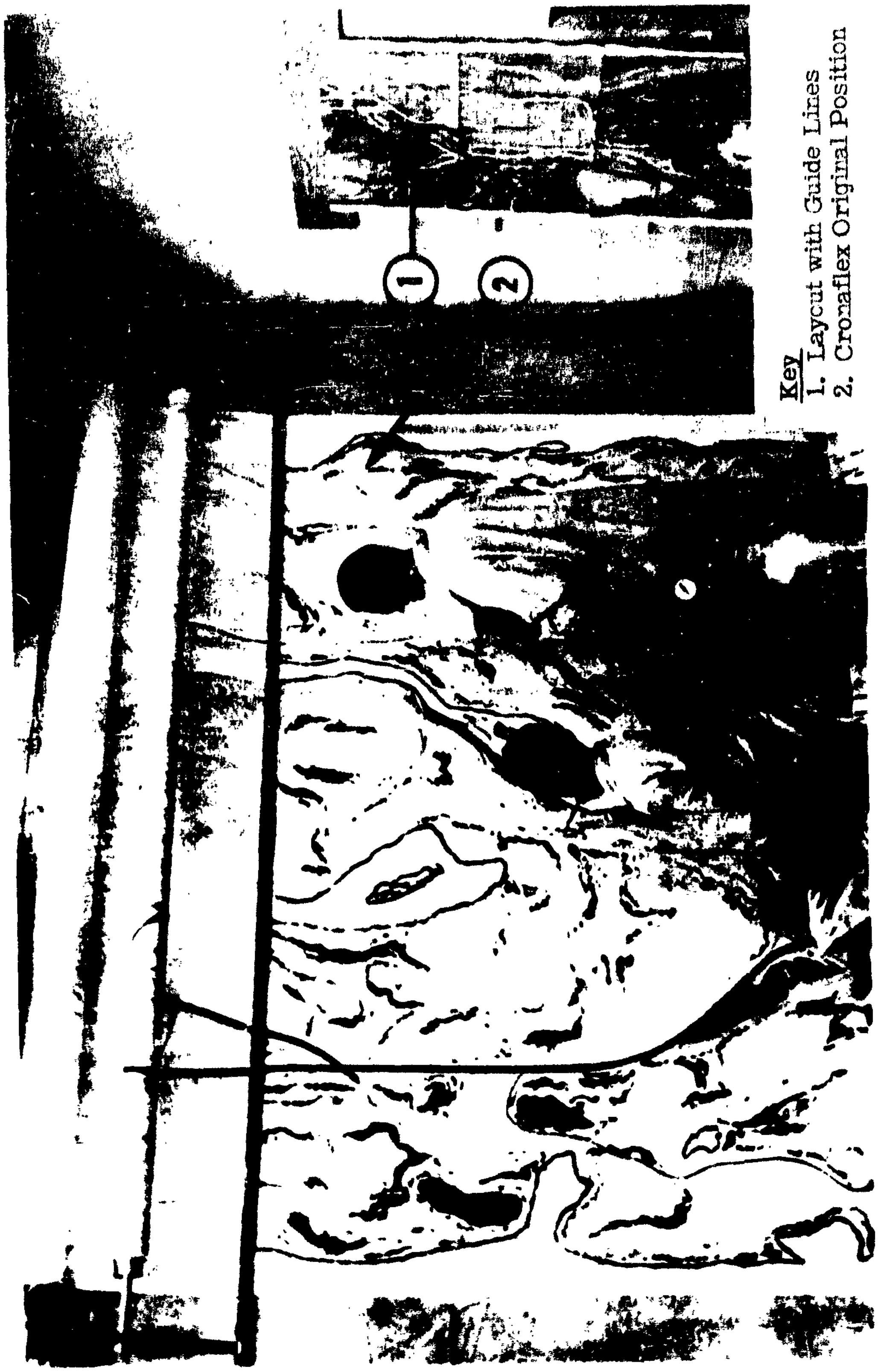
(h.) Dyeing the combined transparency as shown in Figure 4-9. A completed transparency section is shown in Figure 4-10.

4.4.7 To simplify the manufacture of transparencies, an investigation is presently being conducted to determine the possibility of producing positives directly from positives, thus eliminating the negative step. This appears to be possible by using a duPont positive print material which can be handled in ordinary subdued light conditions during exposure and development.

4.4.8 To obtain an effect similar to the continuous tone obtained

Figure 4-5 Sectionalized Original Art Work for Reproduction to Another Scale Ratio

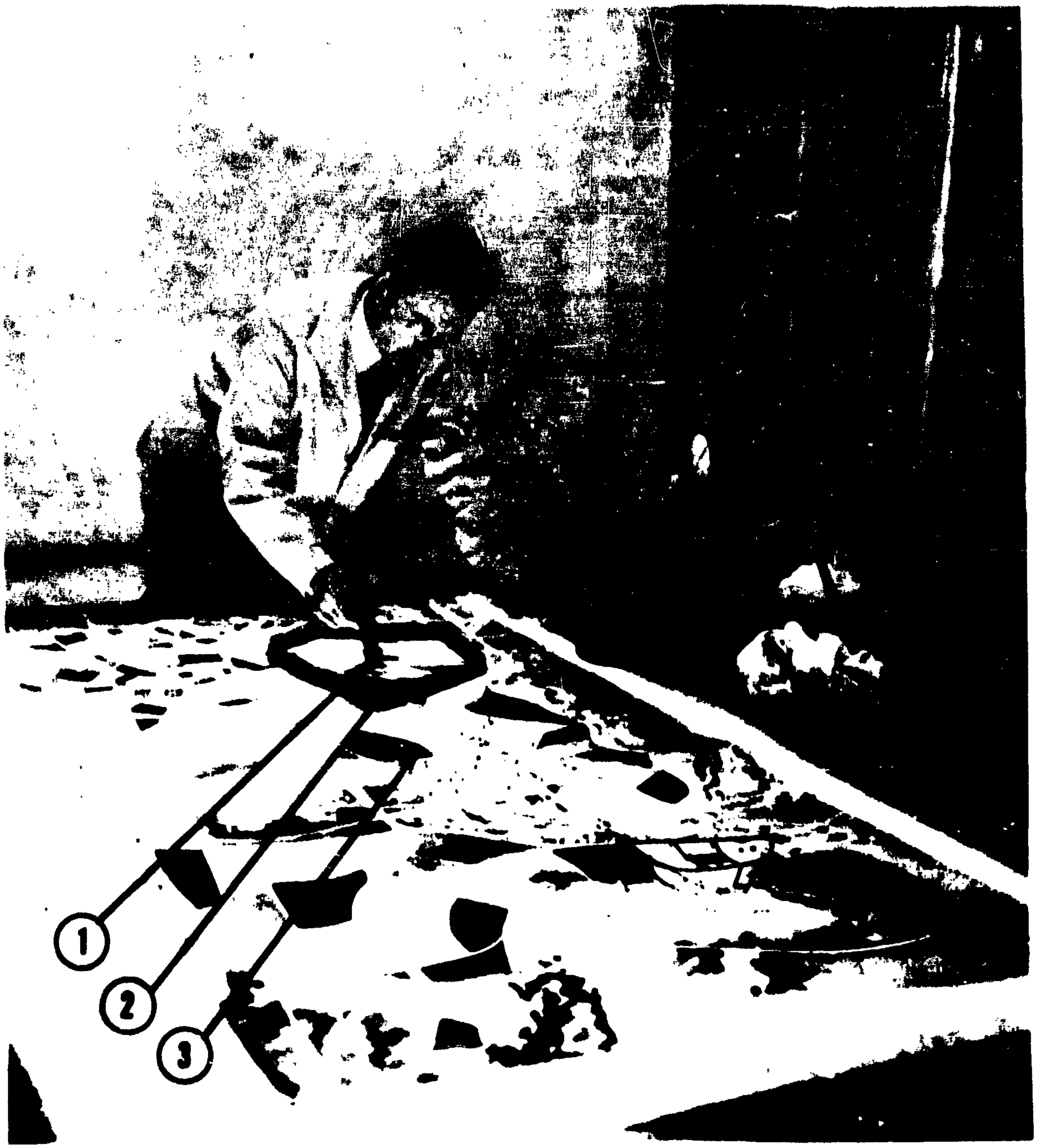
Figure 4-6 Layout of Guide Lines to Scale of Final Transparency



Key
1. Laycut with Guide Lines
2. Cronaflex Original Position

Figure 4-7 Masking Cronaflex Original Prior to Airbrushing

Figure 4-8 Section of Airbrushed Original Positive Made on Translucent Cronaflex



Key
1. Suction Tube for Removal of Dye
2. Clay Barrier Around Dyed Area
3. Transparency

Figure 4-9 Dyeing Transparency by Dip Dyeing Techniques

Figure 4-10 Photographic Transparency (Original is in Full Color)

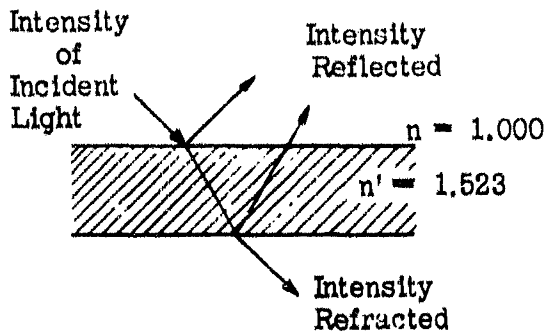
with photographic transparencies, a special technique was utilized in manufacturing a rigid transparency for Device 2-FH-2 which combined photographic and hand decorated techniques. Briefly, the system consists of dyeing the plate by the standard methods and then applying a special photographic coating over the dyed areas to obtain the simulated continuous tone effects. This was done by applying a resin over the entire plate and coating the resin with a light sensitive material. Positives of the photographic image desired (continuous tone and line detail) were placed in proper registration over the dyed areas and exposed to light. The exposed areas then became impervious to certain solutions and the unexposed areas were washed away, leaving a photographic image consisting of a resin residue. This method made possible the inclusion of fine detail otherwise impossible by hand decorated techniques. The photographic work in this instance was sub-contracted to the Truline Corporation, Saint Louis, Missouri.

4.5 Light Transmission Qualities of Transparent Materials

4.5.1 It is in order to discuss the light transmission characteristics of plastics since this subject has a rather profound influence on the point source projection technique, especially in applications where low simulated altitudes are involved or where there is a requirement for the projection of distant scenery.

4.5.2 A limitation of the point source projection technique is its inability to project distant scenery, if the transparency is perfectly flat (which is a condition for good perspective if the area to be portrayed is flat). For all practical purposes, light transmission is reduced to a small amount at angles of 85° of incident light. This means that all scenery beyond ten times the apparent altitude is not projected. This condition is radically different from what is normally experienced in true life since most of the scenery an observer sees is subtended by the first few degrees measured from the horizontal. Contouring the transparency so that light incident on the distant scenery will never exceed this flat angle will help to relieve this condition. This can easily be done with flexible materials. Rigid materials must be permanently formed.

4.5.3 Most materials used for the transparency base have indices of refraction of about 1.5. Very little light loss occurs in the materials due to absorption. Practically all of the light loss is due to the reflection from either the first or second surface. Figure 4-11 is a graph of the light loss occurring from the first surface as a function of the angle of incidence. For angles of incidence less than 70° the light loss is not appreciable. For the first 40° the light loss is about 4% and is approximately 18% at 70°.



% Reflected = Reflected/Incident

% Refracted = Refracted/Incident

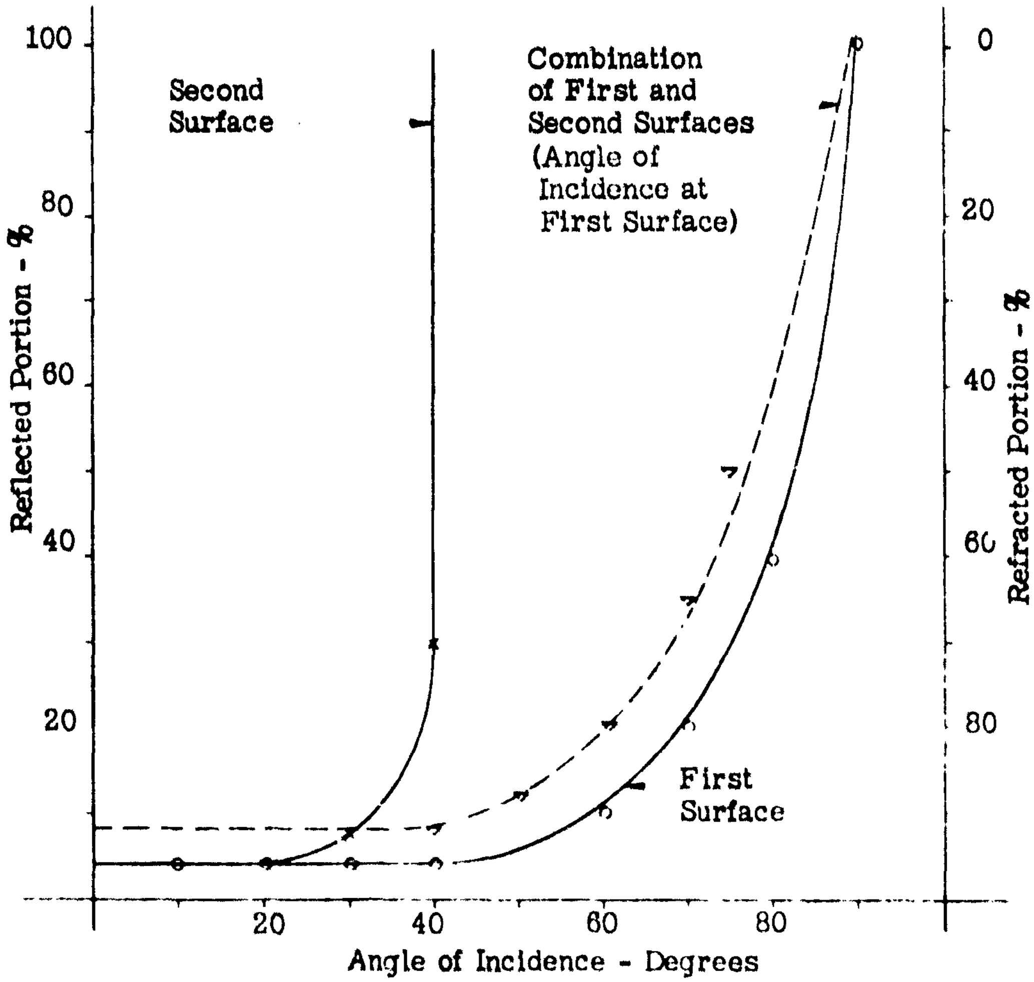


Figure 4-11 - Light Losses Due to Surface Reflection For a Transparent Material With Index of Refraction of 1.523.

After 70° the light loss rises very sharply and is about 70% at 85°. The light that is not reflected from the first surface is refracted following Snell's Law. As the angle of incidence becomes larger and larger, the light is increasingly refracted so that the angle of incidence to the second surface approaches the critical angle for total reflection. As the angle approaches the critical angle, more of the light is reflected and less is refracted so that finally, only a small percentage reaches the screen. Figure 4-11 also indicates the light loss from the second surface and the combined light loss due to reflection from two surfaces. A method is now under study for possibly reducing the light loss due to reflected light from rigid flat Plexiglas by providing one or more surfaces resembling the surface of Fresnel lens (surface configuration very much reduced.) This technique may be applicable to certain projection problems. Fabrication of the surface described will probably present a few manufacturing as well as projection difficulties which will have to be solved.

4.5.4 The light reflections off the transparency surface can be a source of trouble. The reflections are directed to the screen and interfere with the proper transparency projection. The reflected light is partially polarized in the plane of the reflecting surface, and its effect on the projection can be reduced by introducing a filter (plane polarizing material oriented at right angles to the reflecting plane) in the path of the reflected light.

4.5.5 Several successful attempts were made to coat Plexiglas surfaces with anti-reflection coatings, but this only improved the light transmission for small incident angles and had no measurable effect at the larger angles.

4.6 Special Effects

4.6.1 The use of three-dimensional objects on the transparency has greatly enhanced the effectiveness of the point source projection technique. Changes in the perspective of the objects themselves and with other objects appearing in the scene make for a very realistic and convincing presentation. These three-D objects are generally made of transparent plastic materials, usually rigid, which can be dyed and which will transmit light; however, certain objects have been made from opaque materials and have been considered adequately realistic.

4.6.2 Some contouring of the base material has been attempted to follow the contour of a particular area. This has been done by forming Plexiglas and other rigid types of plastic, but is not considered practical

except for the most gentle contours. Sharp changes in contour are difficult to obtain without the use of forming facilities which invariably result in internal striations or surface "mark-off" (surface abberations), which are practically impossible to eliminate. Contouring the entire transparency is primarily used to improve light transmission and rigidity, as previously described, rather than simulating a specific terrain.

4.6.3 Special 3-D objects, such as mountains, have been successfully made by hand forming thin acetate material followed by spraying with a transparent plastic spray. The sprayed material hardens preserving the shape producing mountains as shown in Figure 4-12. This method is very flexible and does not require any forming facilities. Another method which has been used successfully to make satisfactory mountains is accomplished by vacuum forming semi-flexible vinylite. Mountains made by this method are shown in Figure 4-13.

4.6.4 After forming, these mountains must be colored by painting or dyeing. A fair measure of skill is required since the mountains must transmit sufficient light to indicate contours, but cannot be so transparent that the mountain does not appear in the display-image. The color saturation must be sufficient to allow transmission of light through only one side of the mountain. After dyeing, the mountains are cemented to the transparency.

4.6.5 Another special effect that can sometimes be used to indicate surface depressions or crevices is the use of "inverted mountains" mounted upside-down on the lower side of the transparency. Considerable skill must be used to dye the "crevice" and surrounding area to obtain realistic effects.

4.6.6 Several attempts were made to cast three-dimensional mountains from liquid Plexiglas material. The finished products were too dense to transmit light and were not considered successful.

4.7 Aerial Photographs as Transparent Display-Objects

4.7.1 The use of direct aerial photographs as display-objects for point light source projection techniques has only met with mediocre success thus far. The primary reasons for this are as follows:

(a.) Aerial photographs contain considerable minute detail which is not capable of being resolved by the point light source. Substantial improvements in present day point light sources will be required before direct aerial photographs can be used. Such im-

Figure 4-12 "Mountains" Made by Hand Forming Flexible Acetate

Figure 4-13 "Mountains" Made by Vacuum Forming Semi-Flexible Vinylite

provements are not expected in the near future.

(b.) Direct color transparencies are far too dense to be utilized by present day point light sources.

(c.) Direct aerial photographs are never perfect plan views as are those manufactured by the usual methods. Consequently, perspective distortion results.

(d.) Aerial photographs are limited in size, and therefore, registration of smaller sections in the manufacture of a large transparency presents difficult problems.

4.8 Reflective Display-Object

4.8.1 During the study an effort was made to find other types of transparencies which would permit the observer to see greater distances. The reader should recall that a limitation on visibility results from the fact that light is reflected from the surface of the transparencies at acute angles.

4.8.2 This limitation can be used to advantage in certain cases involving transparencies which do not require a large number of three-dimensional objects of well-defined shapes. It has been found that suitable projection plates can be made under these conditions by mirrorizing a sheet of Plexiglas or acetate so that a highly reflective coating is obtained. On this surface is painted, with transparent inks, suitable terrain information. Projection is accomplished with conventional point sources, except for the following changes. The projection plate is inverted and suspended over the observer so that it possesses the usual degrees of freedom. However, the point source is between the observer and the plate. This is shown in Figure 2-4. The scenery is applied to the plate as a mirror image of the normal presentation used in the decoration of transparent plates.

4.8.3 The particular advantage of this projection plate in a point source projection system is that visability is not limited at acute angles of incident light, since the system depends on total reflection. Distant scenery, which would normally be "blacked-out" with conventional transparencies, can now be projected.

4.8.4 However, several disadvantages exist with these transparencies. The most important is the fact that three-dimensional objects of regular shape project on the screen as a double image: the correct image, and directly underneath, an inverted image. This is a result of the interference of light rays from the area directly in front of the object with the object itself, as shown in Figure 4-14. With irregular objects, such as non-descript foliage, the double image is not important if the foliage is reduced to half its scaled size. Its projection will be of proper size and it is difficult for the observer to detect the fact that he is seeing an inverted image along with the upright image.

4.8.5 In addition to this defect, distortions are introduced which are greater than the distortions with transparent plates. This is a result of the increased source to eye displacement. The virtual image of the source, which is the point from which the projection appears to emanate, is actually twice the distance from the light source to transparency plus the distance from the light source to the observer's eye. This added distance causes greater distortions to appear in the projected picture, as described in Chapter 2 on screen distortions.

4.8.6 Another difficulty encountered with this projection plate is the fact that the mirrorized surface will not withstand much abuse. In fact, it is almost impossible to remove inks once they are applied to the surface, since solvents and rubbing of the mirrorized surface will cause a removal of the surface. In addition, masking becomes a problem since the adhesive of the masking tape generally lifts off the silvered surface. Various methods have been investigated for obtaining better adhesion for the reflective coating (actually aluminum), and the Plexiglas. The methods included application of aluminum vapor in a vacuum, and also application by spraying, but neither method showed appreciable improvement over the other.

4.8.7 Methods have been investigated on the possibility of applying inks to the plastic side opposite to the reflective surface in instances where the plastic is extremely thin. However, even then picture quality suffers because of the double image which is created at acute angles.

4.8.8 More extensive investigation of reflective display-objects is currently in progress.

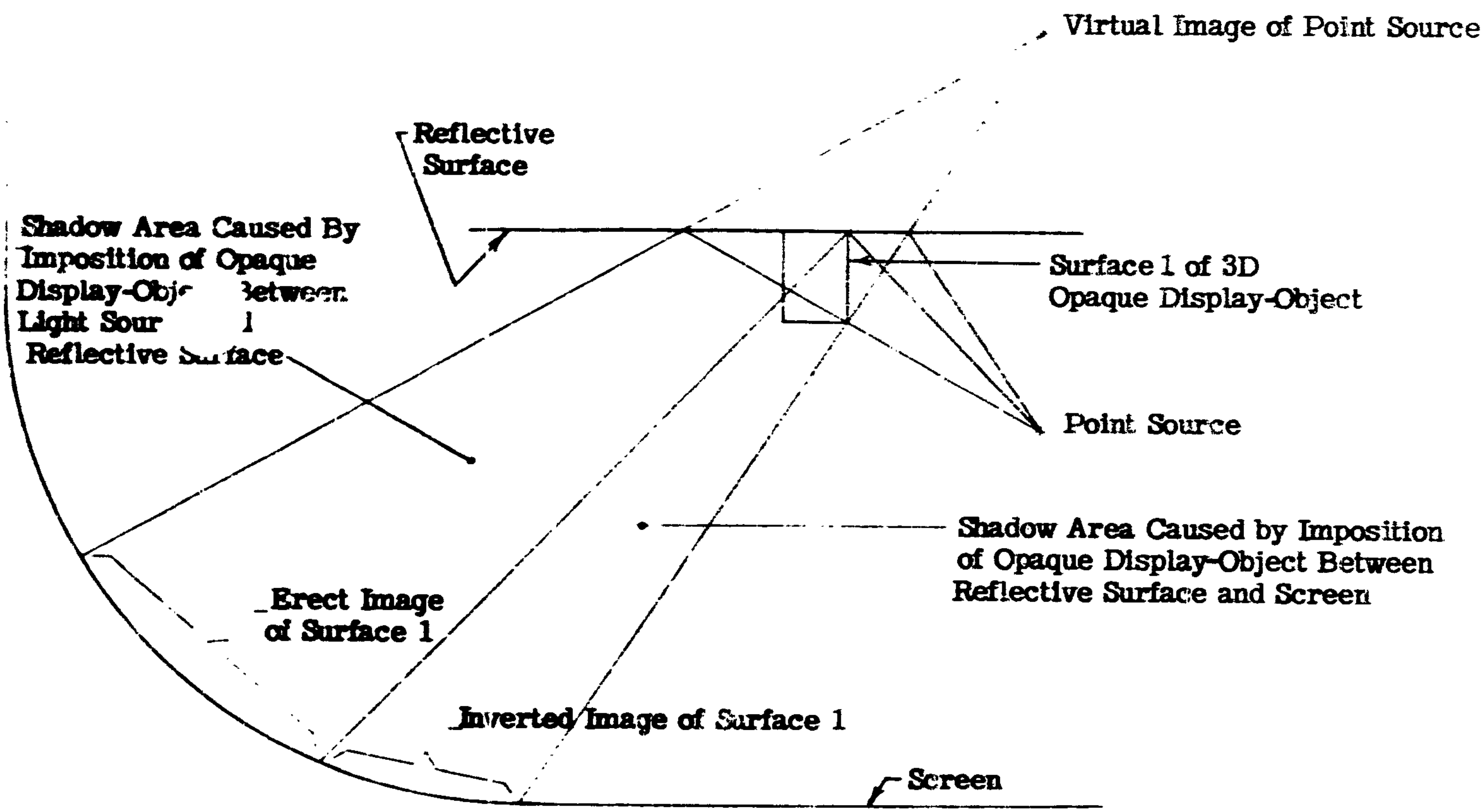


Figure 4 - 14 - Schematic Diagram Showing the Double Image Effect Encountered When a Three Dimensional Object Mounted on Reflective Display-Object is Projected.

CHAPTER 5

The Screen

5.1 Introduction

5.1.1 This chapter deals primarily with the brightness of the display-image and the method in which brightness is affected by the type of screen surface utilized. It describes the various types of screen surfaces generally available, their characteristics, and advantages and disadvantages for point source projection. A method for making a satisfactory screen with a glass beaded reflective surface is described. At the present time this method appears to be most suitable for point source work.

5.1.2 The effect of the screen contour on distortions in the display-image will not be included in this chapter since it has been treated in Chapter 2. It is important to note, however, that the screen design usually requires that several compromises be made. On the one hand the screen should be large to minimize the distortion which results from the displacement between the observer's eye and the source. In addition, a large diameter screen reduces the effects of binocular convergence and the rate of change in binocular convergence with changes in scenery position. A large screen also minimizes the apparentness of the screen grain. On the other hand, the screen should be made as small as possible so that the screen brightness is adequate and to minimize the space requirements of the device.

5.1.3 No data is available which indicates the minimum screen brightness required for training purposes. However, it is substantially less than that required for motion picture theaters which generally maintain a minimum of 5 to 15 foot-lamberts in the highlight areas of the projected display. It has been generally believed by the de Florez Company that anywhere between .2 and .5 of a foot-lambert is sufficient for training purposes, if the observer is dark adapted. The values stated presuppose the use of a low density display-object.. Contrast between the highlights and the shadow areas of the display-object should not be great to insure adequate brightness of the shadow areas. Because of this and the use of pastel colors in the manufacture of a display-object, the over-all impression

that an observer receives when viewing the display image is that the scene is illuminated by low contrast, low brightness daylight conditions resembling a cloudy day.

5.2 Screen Brightness

5.2.1 Screen brightness is determined by several factors, among them the light output of the source, the absorption characteristics of the display-object, the reflective characteristics of the screen itself and its distance from the source. The problem of screen brightness is rendered particularly acute by the fact that a logarithmic relationship exists between variations in absolute brightness level and corresponding variations in the observer's sensory perception. Thus a relatively large increase in the measured value of screen brightness appears to the observer as a small increase of brightness in the display-image viewed. Efforts made to improve the characteristics of the point source and display-objects have been discussed in previous chapters. The reflectivity characteristics of the screen will be discussed in the following paragraphs.

5.3 Types of Screen Surfaces

5.3.1 Several types of screen surfaces are available for use with projection systems. These include:

(a.) Matte, or diffusing type surfaces

(b.) Directional, or specular reflection type surfaces

5.3.2 Matte surfaces will reflect light equally in all directions. Consequently, they are the least brilliant, but are most suitable for viewing from the widest angle. Large theaters make use of this type of surface extensively. The surface is smooth and consequently pictures appear sharp even at short viewing distances.

5.3.3 The specular reflection, or retro-directive type surfaces do not reflect light equally in all directions but favor a particular direction. Thus, an observer sitting within the limits of the most favorable viewing angle will observe a picture brightness which is substantially in excess of that obtained with a matte type surface. The measure of brightness increase over that of a matte surface is generally described as the "gain" of the screen material.

5.3.4 Obviously, if an observer is seated outside the limits of the most favorable viewing angle, picture brightness will be decidedly less than at the favorable angle. It will probably be less than the brightness of the display when projected on a matte surface. Consequently, its gain will be less than one.

5.3.5 For the point source projection system the retro-directive type screen surfaces are to be preferred since the positional relationship between light source, screen and observer is generally fixed and the technique of retro-directive reflection can be applied.

5.3.6 The more common types of specular screen surfaces are the glass beaded type, the metallic type, and, more recently, the lenticular type. The most favorable type for point source projection appears to be the glass beaded type. This type of screen is made by coating the screen surface with a white adhesive, and then pressing or spraying tiny spherical glass beads into it. In this sense it is the first lenticular screen, each bead being a minute spherical lens which is made to return light along a particular direction. A ray of light falling on a glass bead is returned, after several refractions and reflections internal to the glass bead, within a cone of light whose axis is the ray of light falling on the bead. The return cone angle is controlled largely by the index of refraction of the glass bead, being smaller for the larger indices. Within the cone, glass beaded screens give gains of approximately two.

5.3.7 Glass beaded screens are particularly suitable when curved screen surfaces are employed. Curving the surface has very little effect on the return cone since the performance of the spherical bead is unchanged, even with curved surfaces.

5.3.8 The surface texture of the beaded surface is quite coarse. Because of this pictures appear unsharp when viewed from short distances (less than about 6'). From further back, however, the texture is not noticeable. In order to reduce binocular convergence and distortion effects, a screen radius is seldom less than 10' in a point source projection system.

5.3.9 Metallic screens have been tried and have only provided moderate success with the point light source technique. Under favorable conditions screen gains between 2 and 6 can be obtained, but the return cone angle is generally very narrow, thus barring the use of this type of surface where there is a large displacement between light source and observer. In addition,

gain is markedly reduced when curved surfaces are employed, since the return angle is greatly affected by the orientation of the reflecting plane at the point where the ray strikes the plane. Also, wide differences occur in the characteristics of metallic screens. Some are simply made by silver coating a smooth base and others employ a fine silver particle suspended within a thin plastic layer. Size and distribution of the particles is a major factor in determining a silver screen's gain. Another factor is the treatment of the screen surface after the metallic coating has been applied. Metallic screens are generally smooth and sharp detail can be resolved even from a close viewing distance.

5.3.10 Lenticular screen surfaces are the most recent development in the field of screen design. The screen surface is embossed with a pattern of tiny lenses, many thousands of them, which are made to control the light return angle within very close limits. These screens were first made by utilizing metallic screens having special reflective characteristics and then embossing a particular pattern which caused light to be reflected in the desired manner. Theoretically, screen gains as high as 100 or more are possible with this type of screen, but they are generally very expensive to make, and even more important, are generally only suitable with spherical screen sections. Any other type of curvature would require a variable lenticular pattern to control the return path, thus making the cost prohibitively high for point source work.

5.3.11 Typical curves of screen gain versus viewing angle are shown in Figures 5-1 through 5-4 for matte, beaded, metallic, and lenticular screens respectively. A test stand for measuring screen gains is shown in Figure 5-5.

5.3.12 A special matte type surface worthy of mention is the flat rear projection type of screen. The use of this screen is required where rear projection systems are used. This system can be used to advantage to minimize distortion by making it possible to place the observer's eye at a position which is the mirror image of the source position relative to the screen. However, in addition to lower light transmission, which reduces the screen brightness, additional problems must be resolved, especially for the wide angle illusions. Figures 5-6 and 5-7 show curves of light transmission and reflectivity respectively for the rear projection screen.

5.4 Fabrication of a Glass Beaded Screen for Point Source Projection

5.4.1 As previously indicated, glass beaded screens are made by first preparing a smooth white surface with a special white binder and pressing

$$\text{Screen Gain} = \frac{\text{Reflected Luminance of Screen Under Test}}{\text{Reflected Luminance of Standard Matte Screen}}$$

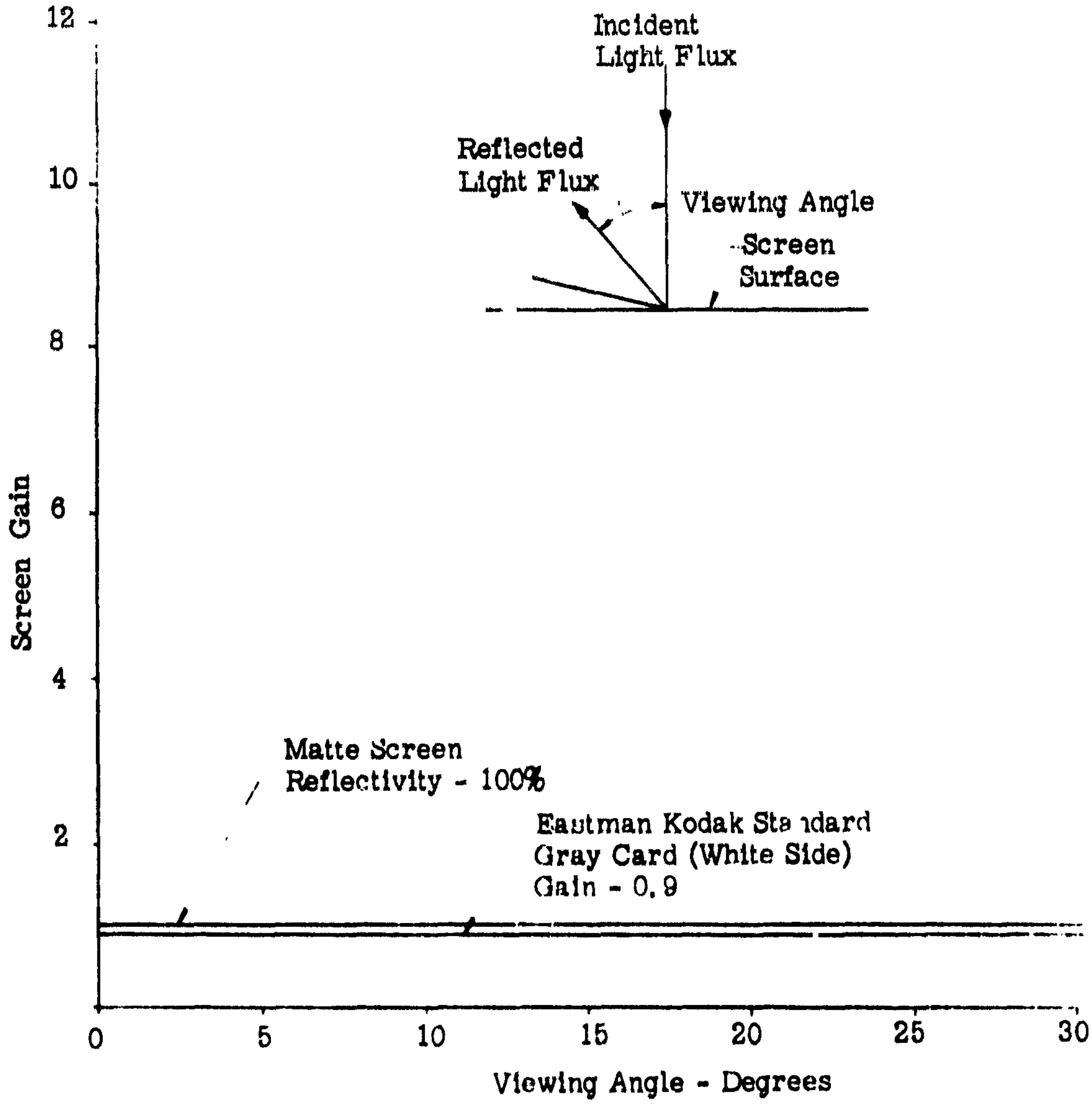


Figure 5 - 1 - Screen Gain with Viewing Angle for a Matte Screen

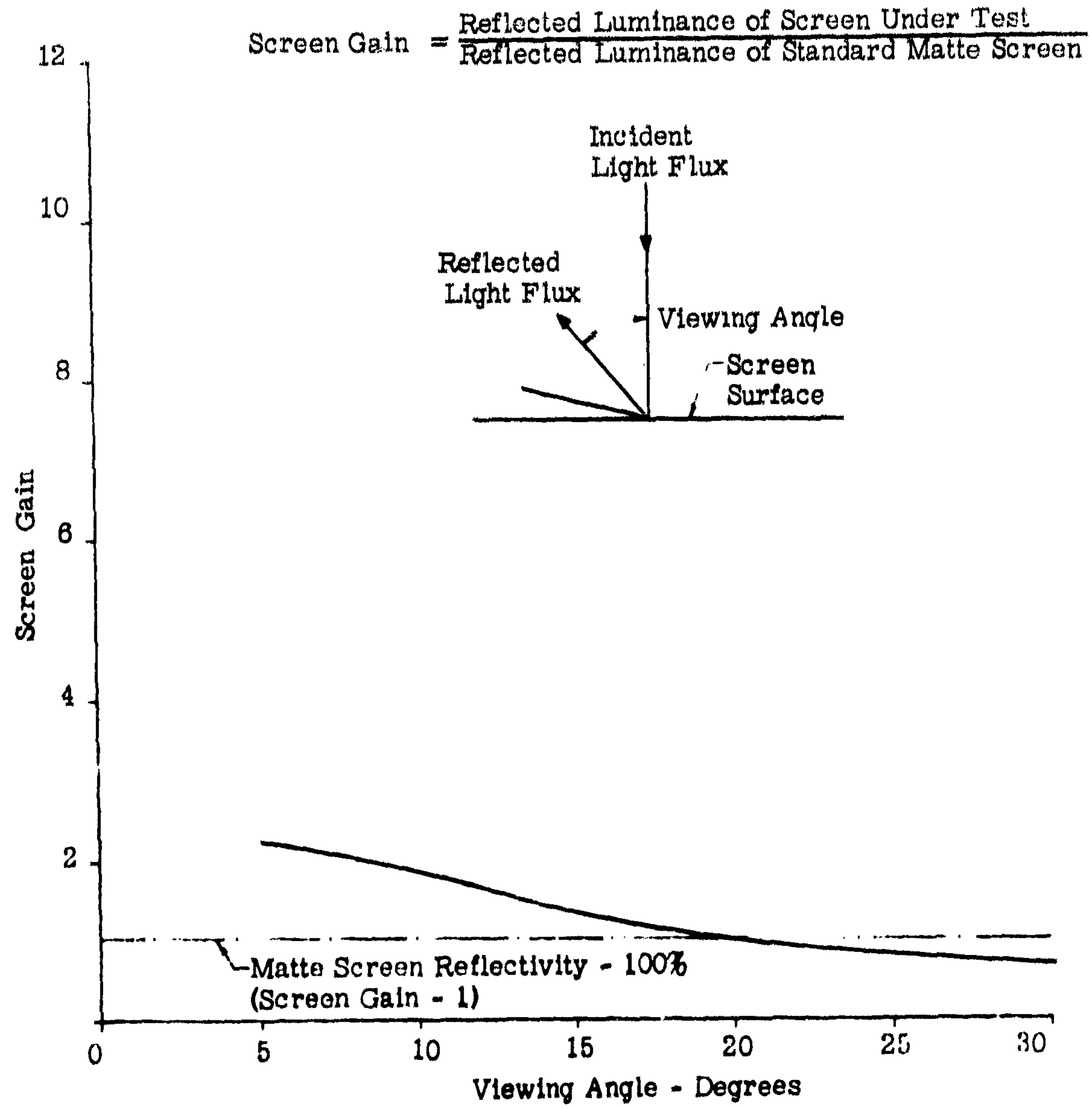


Figure 5-2 - Screen Gain with Viewing Angle for a Da-Lite Glass Beaded Screen

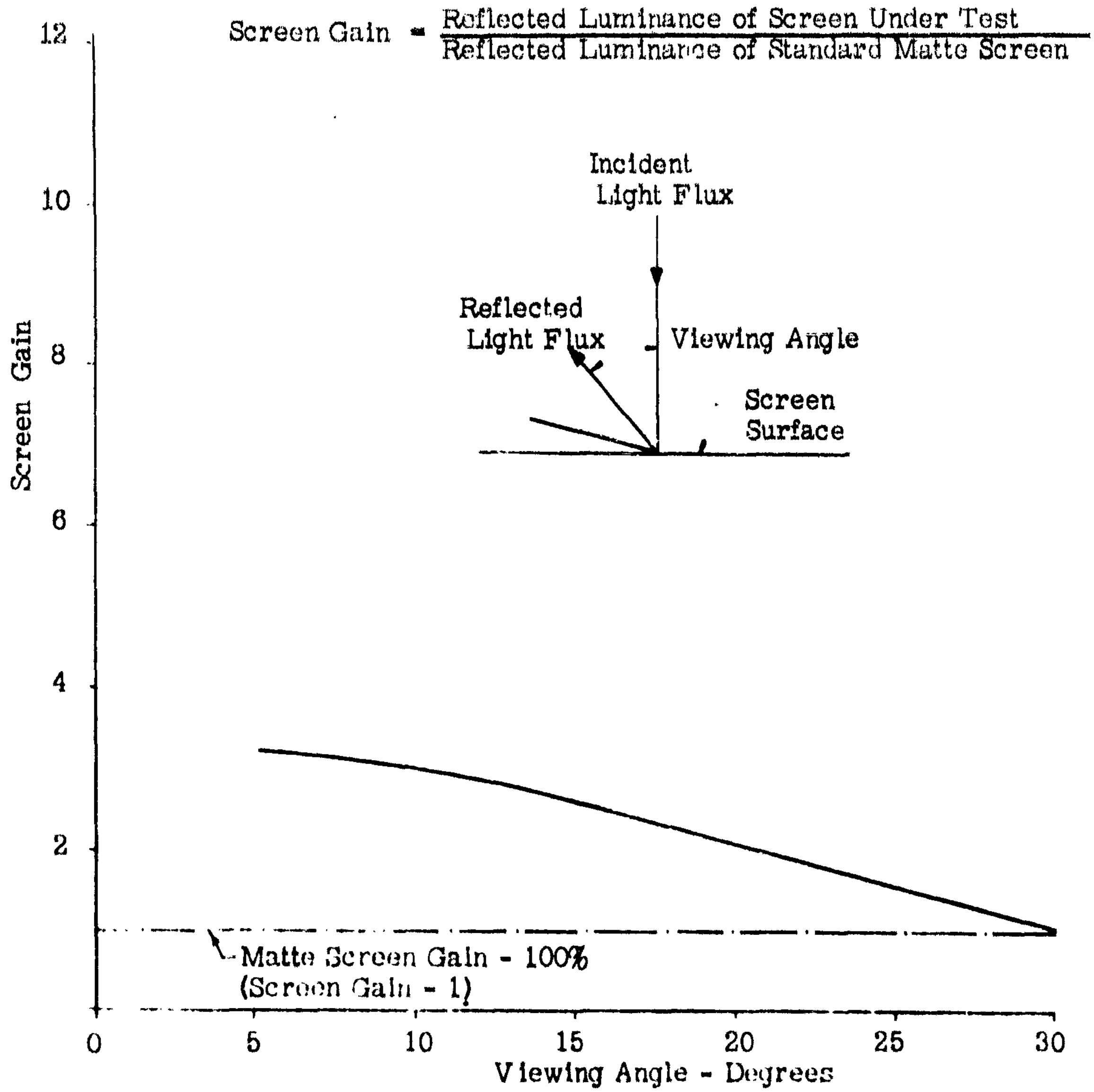


Figure 5-3 - Screen Gain with Viewing Angle for a Radiant Diffuse Metallic Coated "Superama" Screen

Screen Gain = $\frac{\text{Reflected Luminance of Screen Under Test}}{\text{Reflected Luminance of Standard Matte Screen}}$

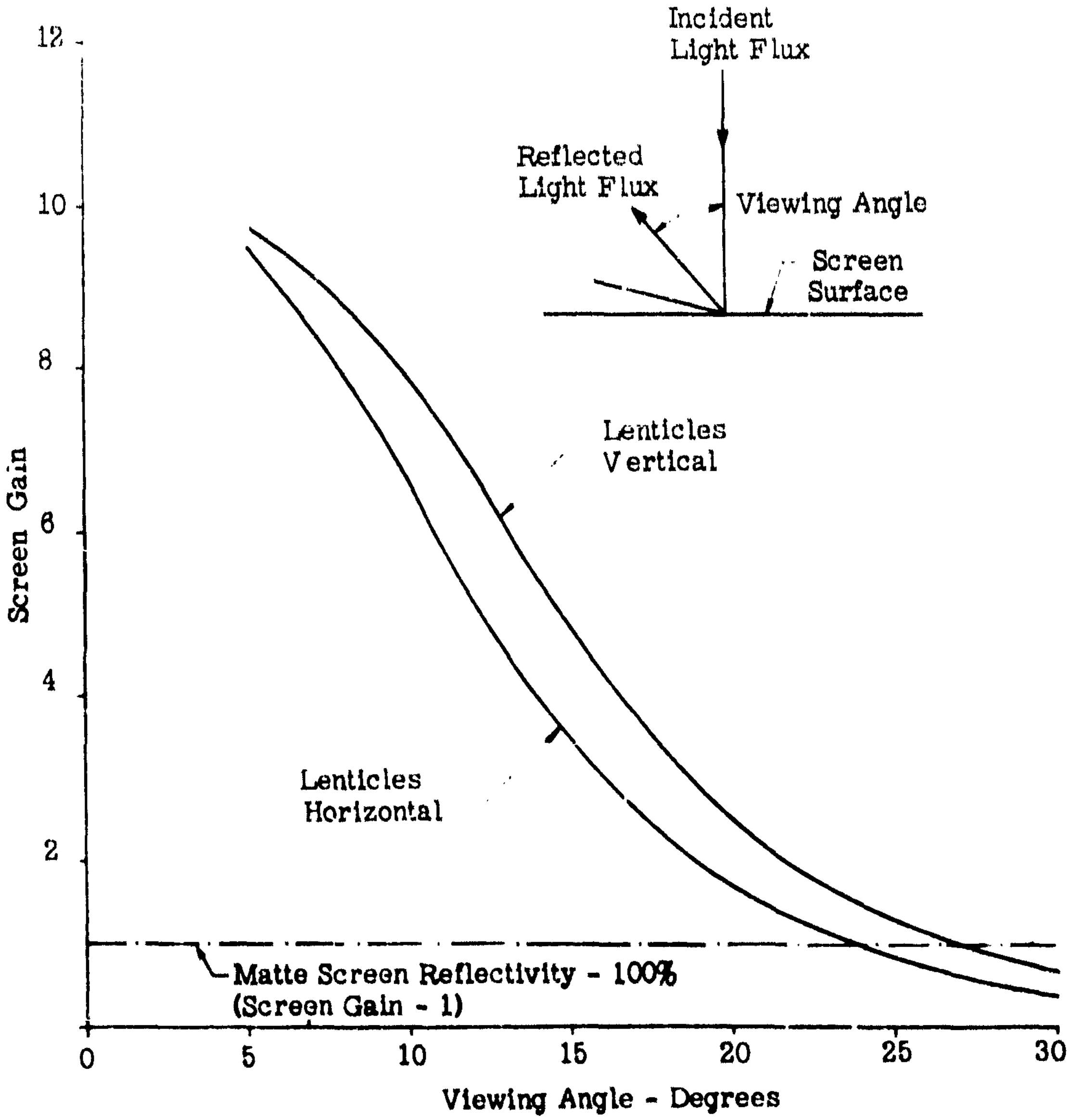


Figure 5-4 - Screen Gain with Viewing Angle for a Nylco Lenticular Screen

Key
1. Screen Sample
2. Mask
3. Light Source
4. Photocell
5. Meter
6. Angular Divisions

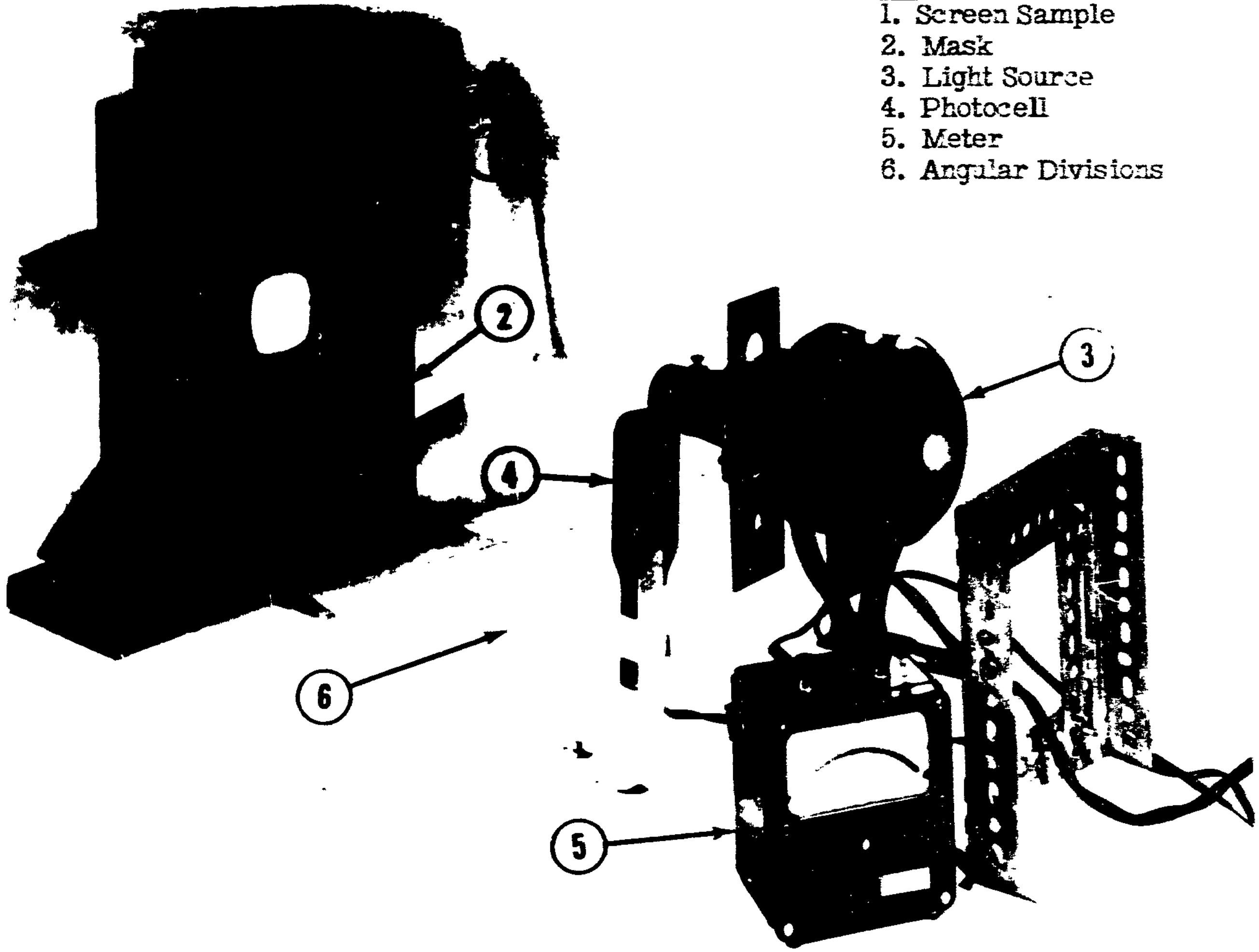


Figure 5-5 Screen Gain Test Apparatus

Source: 25 W Hafnium Lamp - 1.8 Amps.
Screen Type: Rear Projection
Screen Size: 4 inches Diameter
Lamp to Screen Distance: 9 inches
Screen to Photo Cell Distance: 9 inches
Projection Room Condition: Lighttight
Apparatus: Weston Light Meter No. 1246
Determination of Efficiency:

$$\frac{\text{Flux Density to Photo Cell}}{\text{Flux Density to Screen x Screen Area}}$$

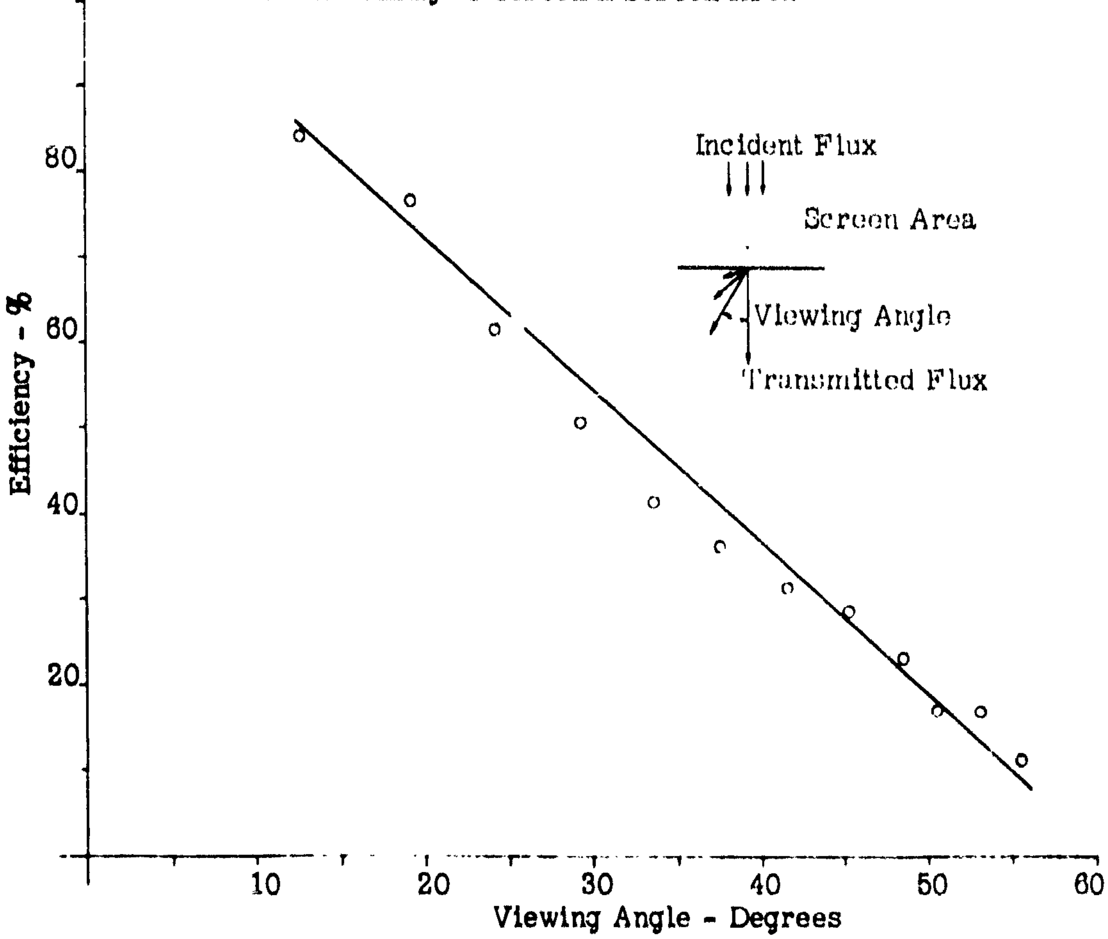


Figure 5-6 - Variation in Light Transmission With Viewing Angle For a Rear Projection Screen.

Source: 25 W Hafnium Lamp - 1.8 Amps.
Screen Type: Rear Projection
Screen Size: 4 inches Diameter
Lamp to Screen Distance: 9 inches
Screen to Photo Cell Distance: 9 inches
Projection Room Condition: Lighttight
Apparatus: Weston Light Meter No. 1246
Determination of Efficiency:

$$\frac{\text{Flux Density to Photo Cell}}{\text{Flux Density to Screen x Screen Area}}$$

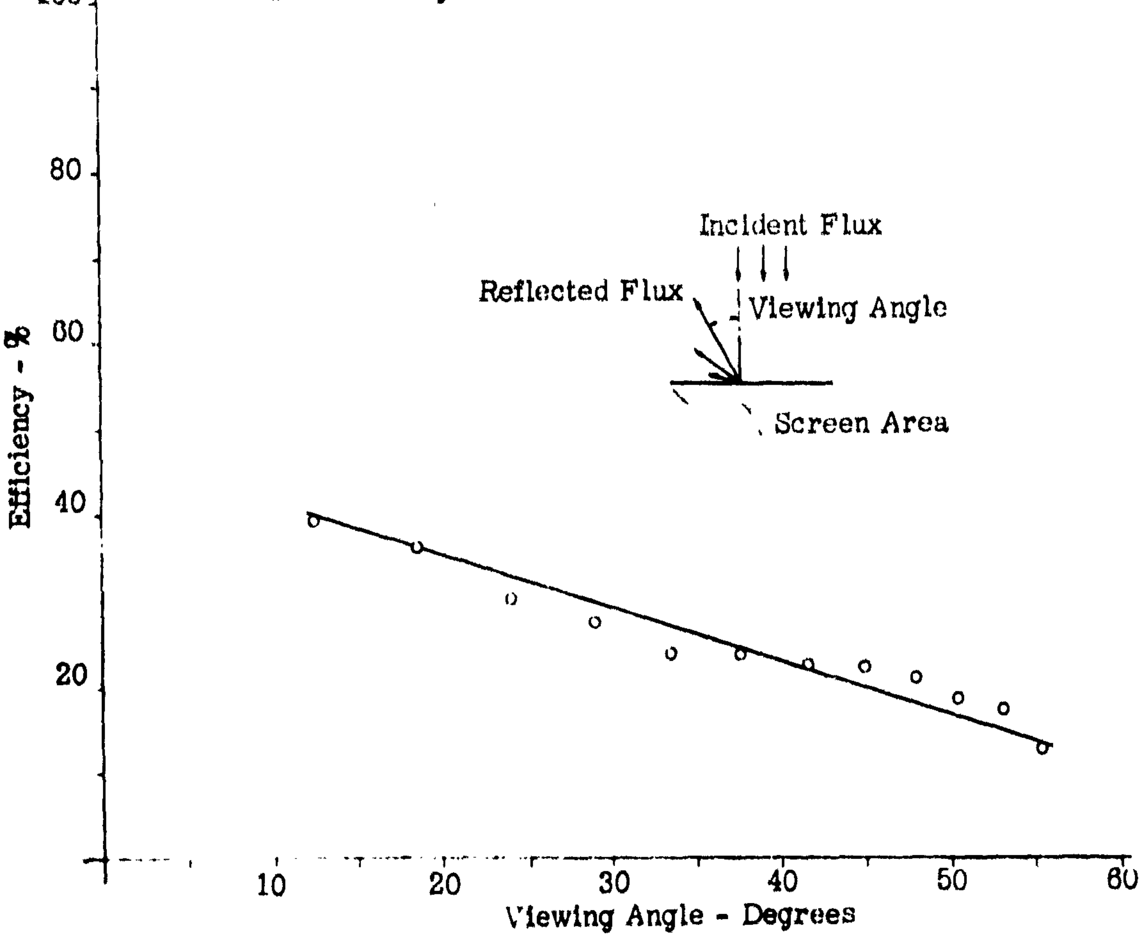


Figure 5-7 - Variation in Light Reflectivity With Viewing Angle For a Rear Projection Screen

or spraying the glass beads to a specific depth into the binder material. The basic rigid structure for the screen can be made of fiberglass reinforced plastic panels joined together and supported from the rear by a light aluminum frame. A schematic representation of this type of design is shown in Figure 5-8.

5.4.2 The various screen panels can be made from a single plaster or wood form, which is actually the negative of the screen panel desired. A typical forming tool is shown in Figure 5-9. After a parting agent is applied to the surface of the forming tool, a thin resin coating is applied to the surface of the tool and subsequent layers of fiberglass sheets and resin, in liquid form, are also applied. Structural ribs can easily be included utilizing this technique. After curing, the rigid panel is removed from the mold. Subsequent panels can be made similarly. The reflective surface is applied to the panel and the screen panels can then be joined together and supported by the aluminum structure to form a continuous surface. Care must be exercised to obtain a continuous surface at the joints. This may require sanding and filling the crevices with special fillers. It has been found possible to reduce the apparentness of the joint by placing a pressure sensitive tape, whose surface has been beaded in a fashion similar to the screen surface, directly over the joint.

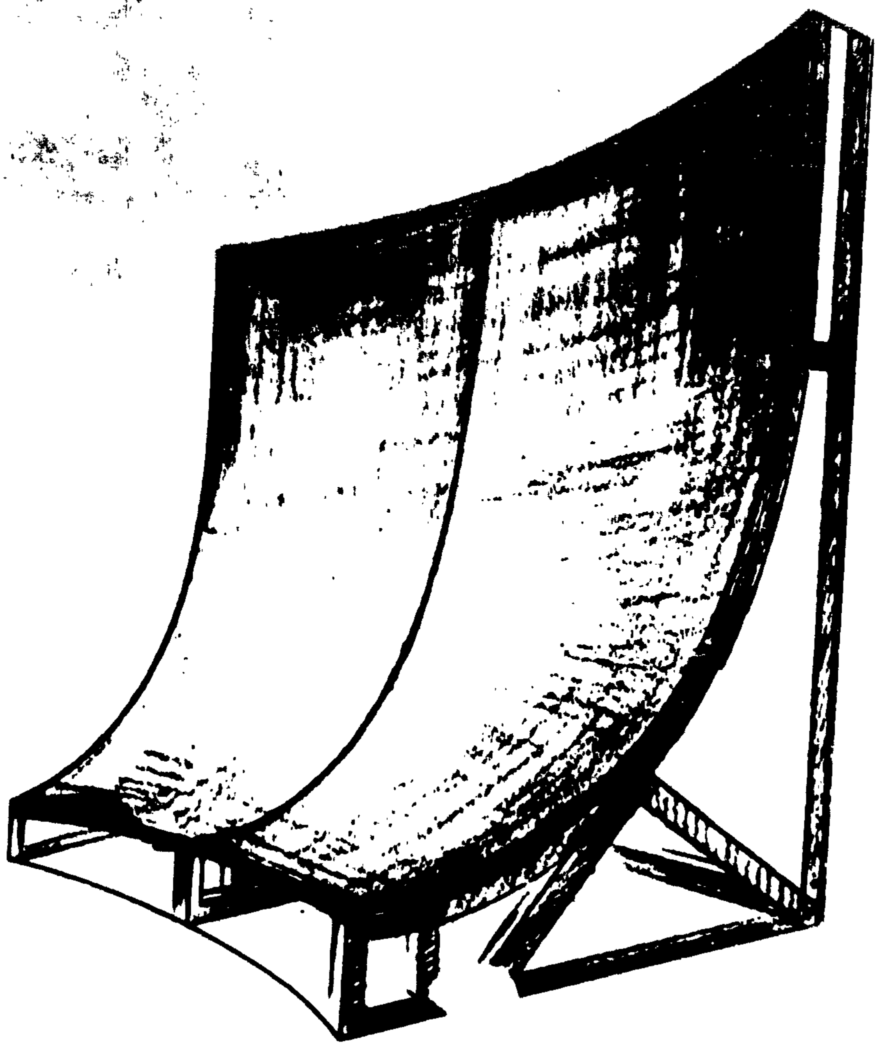


Figure 5-8 Screen Supporting Structure

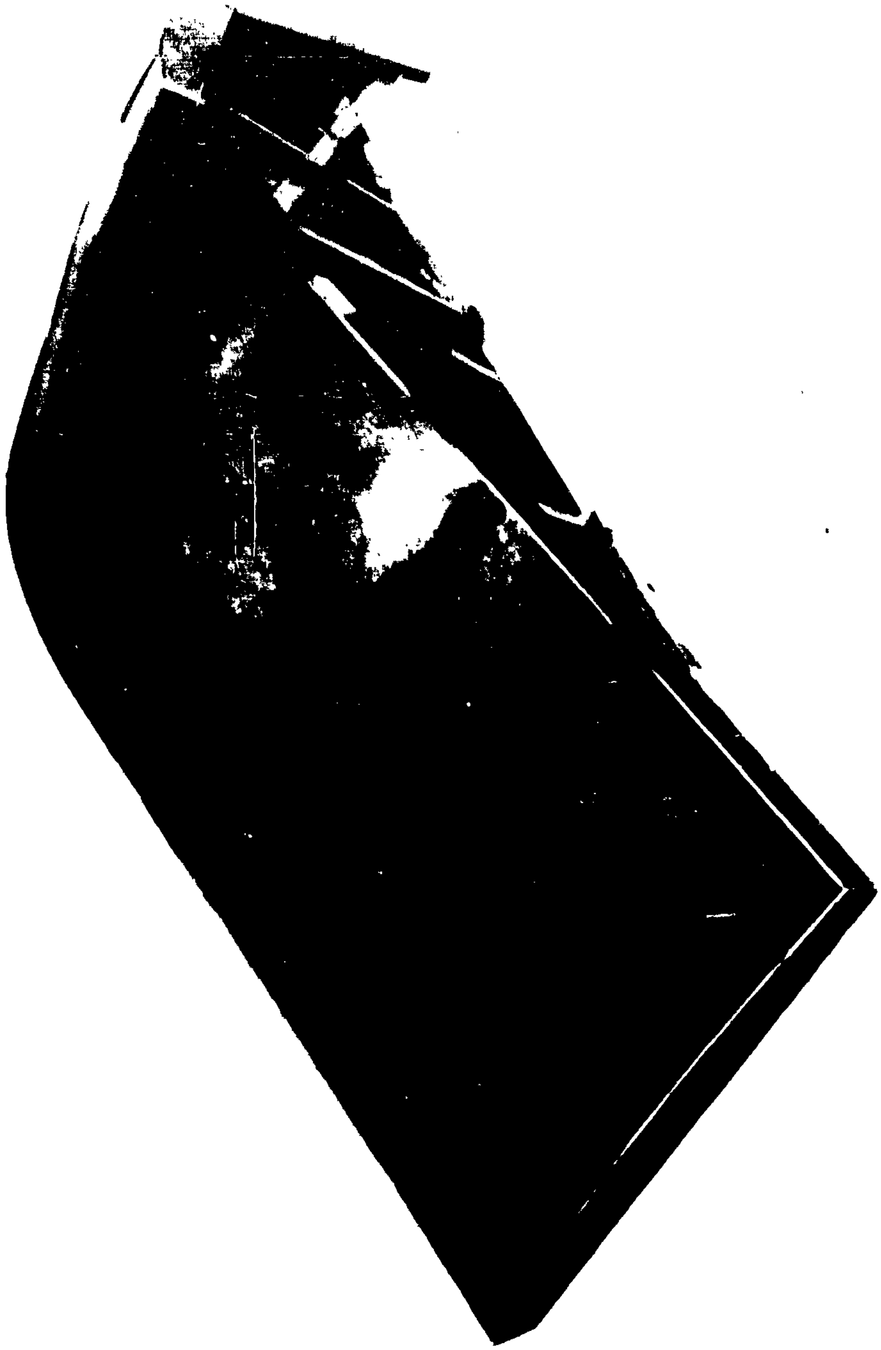


Figure 5-3 A Typical Forming Tool for Fiberglass Reinforced Plastic Panels

CHAPTER 6

Systems Design

6.1 A projection system capable of presenting a non-programmed visual display is invariably a complex device. Therefore, it is essential to limit its versatility from the outset to prevent it from becoming an economic "white elephant" and to insure that the period required for development will not be unduly long. There is a strong tendency for personnel establishing requirements for a device to produce a rigorous specification, generally calling for exact simulation of an operational procedure and greatly complicating the problem. It is therefore important to determine:

(a.) That which is essential to include for training purposes, that which is desirable, and that which being non-essential can be safely excluded.

(b.) The degree of complexity, the cost and the development time that is warranted for the device in proportion to its potential utility for training.

(c.) An estimate of its probable success, that is, its ability to perform in accordance with a specification.

6.2 A careful analysis of the above considerations will generally involve a thorough study of the projection system variables which are closely interrelated. A successful device generally represents the best compromise of these several variables.

(a.) The area to be covered by the display and the configuration of the area.

(b.) The altitude range required.

(c.) The pitch and roll angles to be simulated.

(d.) The definition required within the display.

(e.) The brightness required for the display.

(f.) The vehicle to be simulated, including such characteristics as the visibility from within, its general physical arrangement and configuration.

(g.) The distortions tolerable in the display.

(h.) The total size of the training device.

6.3 Some of the more important considerations which enter into the selection of a scale factor for the transparency include the minimum altitude to be depicted, the total area to be simulated and the minimum size of objects to appear in the display. The scale factor, together with the size of the simulated area, generally dictates whether the transparency shall be of the flexible or rigid type. Rigid transparencies generally limit the size of the simulated area while the flexible ones provide greater coverage but complicate the projector. When it becomes necessary to simulate an "on-ground" condition, it is advisable to establish a scale factor of less than 2000:1. If excellent definition in the visual display or detail in the 3-D objects is required for a specific problem, the scale selected generally may not exceed 500:1 although a scale factor of 1000:1 is sometimes possible.

6.4 The ratio of maximum altitude to be simulated to minimum altitude must be no greater than 100:1 and preferably should be less than 50:1. Greater values of this ratio usually result in considerable vertical travel of the point source thereby reducing the visual display brightness and increasing distortions at the maximum altitudes because of the large point source to eye displacement. In the case of a rigid transparency utilizing end plates, the horizon line is considerably raised with large vertical travels of the source. The actual source travel should not exceed 6 to 10 inches.

6.5 Due to the extensive size of the transparency, of the projector support mechanism, and of the associated drive systems for obtaining the six degrees of freedom, pitch and roll angles should generally be limited to $\pm 20^\circ$. Values in excess of this usually place a tremendous burden on the power servos required for the device and greatly complicate the projector suspension and drive mechanisms. Higher values also restrict the visibility of the pilot when the projector is in an inclined position.

6.6 The cockpit configuration also plays an important role in pilot visibility. Obviously visibility can be no better than in the actual aircraft if true simulation is to be achieved. Generally, simulated visibility is poorer than actual conditions since it is not always possible to obtain the total angular coverage both horizontally and vertically. Direct shadows of the cockpit, which fall within the usual areas of visibility, often restrict coverage. In the event the cockpit configuration provides for an instrument panel directly over the pilot's head, it is impossible to cut away any of the overhead structure of the cockpit, thereby increasing the source to eye displacement and the accompanying distortions.

6.7 As indicated in Chapter 5, selection of the screen radius is based on the brightness that is required for the display, the distortions tolerable in the display and the total room size that is available for the training device. The various binocular effects, of which little is known, also dictate that the screen radius be made as large as practicable. A range of 10 to 20 feet appears to be proper for the projection screen radius for point source systems. A minimum screen brightness for the important areas of approximately .2 of a foot-lambert is required, although it is desirable to increase this value to about .4 if it is practical to do so.

6.8 Summarizing, unless the visual display that is required is extremely simple, it will usually be necessary to sacrifice one or more of the available variables. The compromise which must be made will be dictated by the nature of the training problem and often will spell success or failure for the device.

ABERRATION - a deficiency in an optical system or element caused by convergence to different foci, by a lens or mirror, of rays of light eminating from one and the same point.

ABSORPTION - loss of a portion of the luminous flux incident on a body which is prevented from passing through it.

ANGLE OF INCIDENCE - the angle at the point of incidence, between the direction of incident light and a normal to the surface on which it falls.

ANGLE OF REFRACTION - the angle between the direction of light emerging from a surface and a normal to that surface.

APERTURE - the effective opening for the passage of light rays in an optical system.

APLANATIC - free from spherical aberration and coma.

BRIGHTNESS - see luminance

CANDLE - the photometric unit of luminous intensity. One candle equals one-sixtieth of the luminous intensity of one square centimeter of a hollow enclosure at the temperature of solidifying platinum (1755° C).

COMA - the failure of a lens to image paraxial rays and rays through its outer zones at the same point when the rays originate from points not on the optical axis.

DEFINITION - the sharpness of gradation of the demarcation between distinct areas or between details. (see also resolution)

DEGREES OF FREEDOM - number of variables needed to define position of a body in space. The six degrees of freedom of movement in space are: linear motion along the x, y, and z axes and rotary motion about each of these axes.

DEMAGNIFICATION - see magnification.

DIFFRACTION - the spreading of a beam of light around the edges of an obstruction.

DIFFRACTION ANGLE - the angle between a line drawn from the light source to the edge of an obstruction and the path of the diffracted light.

DISPLAY-IMAGE - the image formed on the screen and presented to the observer's view.

DISPLAY-OBJECT - that design, decoration, pattern, etc. imposed between the light source and the screen to alter the uniformity of the light. The display-object may be transparent or reflective.

ENTRANCE ANGLE - the angle at a point object of a lens on its optical axis subtended by the aperture of the optical system in question.

ENVELOPE - as applied to lamps, the glass, quartz or other transparent bulb enclosing the light emitting parts.

EXIT ANGLE - the angle at a point image on the optical axis of a refracting surface formed by the aperture of the refracting surface.

EXTENDED "POINT" SOURCE - see point source.

EXTENDED SOURCE ANGLE - the angle with its vertex at a line on the display-object subtended by the extreme edges of an extended source.

FOOT-CANDLE - the photometric unit of illumination. One foot-candle is the illumination produced when the luminous flux from one candle falls normally on a surface at a distance of one foot. One foot-candle is numerically equivalent to one lumen per square foot.

FLUX DENSITY - A measure of total quantity of light or illumination.

ILLUMINATION - the illumination of a surface is the amount of luminous flux it receives per unit area. The unit of illumination is the foot-candle.

IMAGE - the picture or counterpart of an object produced by reflection or refraction, or by the passage of rays through a small aperture. An image formed by the actual intersection of light rays is <u>real</u>. An image formed by the apparent (but not actual) intersection of light rays is <u>virtual</u>.

INCIDENT LIGHT - that light which falls on a surface.

INDEX OF REFRACTION - the ratio of the velocity of light in a vacuum to the velocity of light of a particular wave length in any substance is called the index of refraction of the substance for light of that particular wave length. The velocity of light in air is so nearly equal to its velocity in free space, that for most calculations the index of refraction of air can be assumed unity without introducing significant error.

LINE WIDTH - the width of lines which define details on the display-object. This is a measure of the fineness of details on the display-object.

LUMEN - the fundamental photometric unit. One lumen equals the amount of luminous flux radiating by a point source of one candle throughout a solid angle of such size as to surround a unit area at a unit distance from the source. By experiment it has been determined that for a normal observer one lumen is equivalent to 0.00161 watt of monochromatic green light of a wave length of 555 millimicrons, corresponding to the maximum of the visibility curve.

LUMINANCE - the amount of luminous flux radiated per unit of solid angle per unit of area of an extended source. Luminance, also called brightness, is expressed in candles per unit area.

LUMINOUS FLUX - the rate of transfer of visible radiant energy. The unit of flux is the lumen.

LUMINOUS INTENSITY - the amount of luminous flux radiated per unit of solid angle in a given direction by a point source. The unit of intensity is the candle.

MAGNIFICATION - the increase (magnification greater than 1) or decrease (magnification less than 1) in the size of an image as compared to the actual object. Reduction (magnification less than 1) may also be termed demagnification. As applied to the point source system, magnification refers to the enlargement of the display-image over the size of the display-object during projection. The <u>theoretical magnification</u> of the system is the enlargement of the display-image over the display-object size which would be expected if a geometric point source of light were used for projection. As applied to optical components such as lenses, magnification refers to the enlargement or reduction of the image size as compared with the object size. <u>Lateral magnification</u> is this enlargement

as applied to those dimensions in a plane perpendicular to the optical axis. Longitudinal magnification refers to that enlargement of dimensions in planes containing the optical axis.

MENISCUS LENS - a lens having the centers of curvature of both refracting surfaces on the same side.

NEGATIVE LENS - a lens whose thickness at the optical axis is less than its thickness at the periphery.

OPACITY - the reciprocal of transparency.

OPTICAL AXIS - the line connecting the centers of curvature of the refracting surfaces of a lens. The axis of an optical system is the line connecting the centers of curvature and the midpoints of the spherical refracting surfaces which make up the system.

PENUMBRA - the gray portion of a shadow surrounding the umbra; it receives light from some, but not all, parts of the light source.

PHOTOMETRY - the science of measuring light.

POINT LIGHT SOURCE - a small source of light approaching in size the classic geometric definition of a point. A geometric point source is a point source of light conceived as having 0 dimensions. This is a theoretical concept only and cannot be achieved physically. An extended "point" source or simply an extended source, is a point source with finite dimensions.

PROJECTION ANGLE - the angle in a vertical plane, with its vertex at the point source which is subtended by a horizontal line and the line of projection toward any point on the display-image.

REFLECTANCE - the ratio of reflected luminous flux to the total incident flux in percent.

REFLECTION - that portion of luminous flux incident on a body which is deflected by a surface of the body without passing through that surface.

REFRACTION - the change in direction of a wave which results when it enters another medium obliquely and when the velocity of the wave in the second medium is different from its velocity in the original medium.

RESOLUTION - the distinguishing of fine details from one another. Resolving power is the ability to distinguish among fine details and is commonly evaluated by determining ability to distinguish fine points or lines set close together as individual items.

RETRO-DIRECTIVE - the characteristic of being able to return something along the same path by which it came.

SLOPE ANGLE - the angle formed between the optical axis of a lens system and any ray which crosses the optical axis.

SPHERICAL ABERRATION - A deficiency caused by the failure of a lens or mirror to image paraxial rays and rays through outer zones at the same point when the rays originate at a point on the optical axis.

TRANSMISSION - the portion of total luminous flux incident on a body which passes through it.

TRANSMITTANCE - the ratio of transmitted light to incident light in percent.

TRANSPARENCY - the ratio of the intensity of the transmitted light to the intensity of the incident light in percent. Also, a transparent display-object (see display-object).

UMBRA - the totally black portion of a shadow which receives no light from the light source.

VIEWING ANGLE - the angle, in a vertical plane, with its vertex at the eye of the observer which is subtended by a horizontal line and line of sight toward any point on the display-image.

APPENDIX I

Studies of the Distortions of the Display-Image on Basic Screen Shapes Resulting from Displacement of the Eye from the Point Source

I - 1 Position Distortion on a Flat Vertical Screen

By definition, position distortion, η , is

$$\eta = \zeta - \delta \text{ Hence when } \quad \zeta = \delta, \eta = 0 \tag{1}$$

In figure I - 1, let

$$\zeta = \tan^{-1} \frac{Y}{d} \text{ or } \tan\zeta = \frac{Y}{d} \tag{2}$$

$$\delta = \tan^{-1} \left(\frac{Y - v}{d - h}\right) \text{or } \tan\delta = \frac{Y - v}{d - h} \tag{3}$$

Solve (3) for Y and substitute in (2)

$$\zeta = \tan^{-1} \left[\frac{v}{d} + \left(1 - \frac{h}{d}\right) \tan\delta\right] \tag{4}$$

Substitute (4) in (1)

$$\eta = \tan^{-1} \left[\frac{v}{d} + \left(1 - \frac{h}{d}\right) \tan\delta\right] - \delta \tag{5}$$

Let

$$X' = \frac{v}{d} + \left(1 - \frac{h}{d}\right) \tan\delta \tag{6}$$

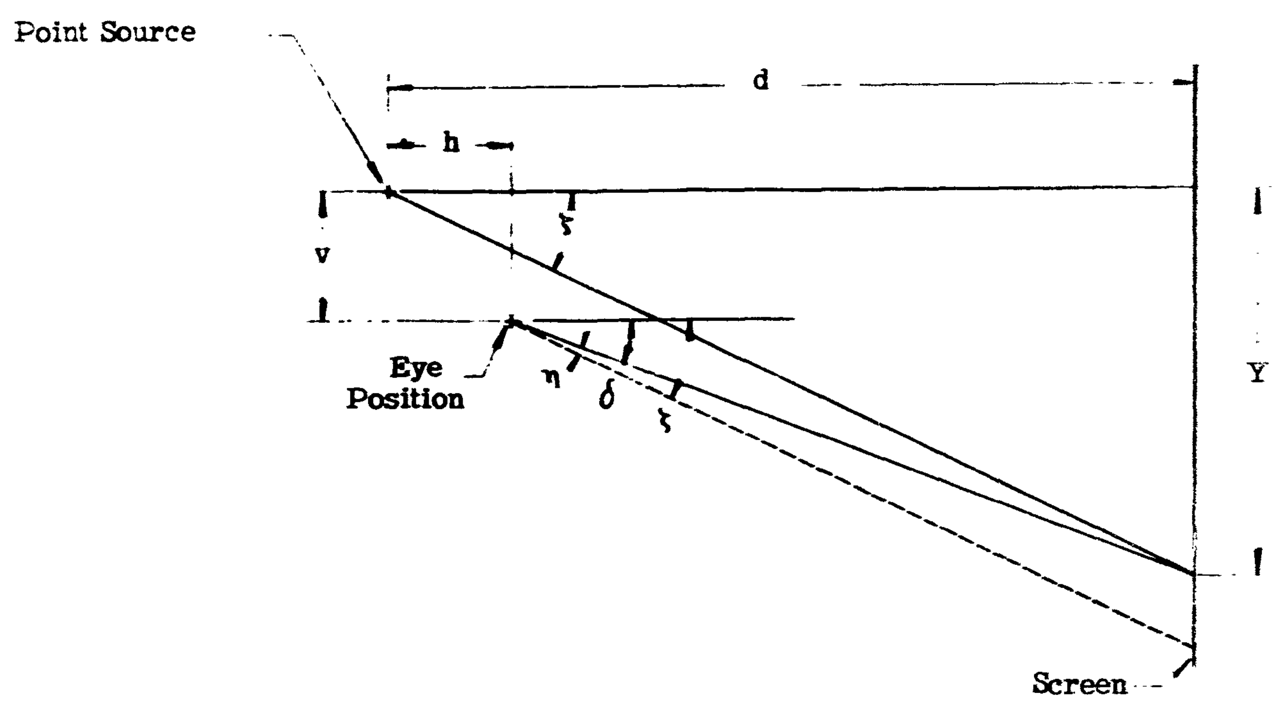


Figure I-1 - Schematic Diagram Showing Position Distortion on a Flat Vertical Screen Resulting From Displacement of the Eye From the Point Source.

Substitute (6) in (5) and differentiate with respect to

$$\frac{d\eta}{d\delta} = \frac{d\tan^{-1}X'}{d\delta} - \frac{d\delta}{d\delta}$$

But

$$\frac{d\tan^{-1}X'}{d\delta} = \frac{1}{1+X'^2}\;\frac{dX'}{d\delta}$$

and

$$\frac{dX'}{d\delta} = \left(1-\frac{h}{d}\right)\sec^2\delta$$

Therefore

$$\frac{d\eta}{d\delta} = \frac{\left(1-\frac{h}{d}\right)\sec^2\delta}{1+\left[\frac{v}{d}+\left(1-\frac{h}{d}\right)\tan\delta\right]^2} - 1 \qquad (7)$$

Position distortion is greatest when $d\eta / d\delta = 0$. (7) then becomes

$$\left(1-\frac{h}{d}\right)\sec^2\delta = 1+\left[\frac{v}{d}+\left(1-\frac{h}{d}\right)\tan\delta\right]^2$$

Substitute the trigonometric identity $1+\tan^2\delta = \sec^2\delta$ and simplify

$$h\left(1-\frac{h}{d}\right)\tan^2\delta - 2v\left(1-\frac{h}{d}\right)\tan\delta = \frac{v^2}{d} + h \qquad (8)$$

For the case where the point source is located directly above the eye, $h = 0$; (8) becomes

$$\delta = \tan^{-1}\left(\frac{-v}{2d}\right) \qquad (9)$$

Substitute (9) in (5)

$$\eta = \tan^{-1}\left[\frac{v}{d} + \frac{-v}{2d}\right] - \tan^{-1}\left(\frac{-v}{2d}\right)$$

But

$$-\tan^{-1}\left(\frac{-v}{2d}\right) = \tan^{-1}\left(\frac{v}{2d}\right)$$

Therefore

$$\eta = 2\tan^{-1}\left(\frac{v}{2d}\right) \qquad (10)$$

I - 2 Position Distortion on a Flat Horizontal Screen

Using figure I - 2, it can be shown by similar reasoning that, for a flat horizontal screen,

$$\eta = \cot^{-1}\left[\frac{h}{d} + \left(1 - \frac{v}{d}\right)\cot\delta\right] - \delta \qquad (11)$$

$$\frac{d\eta}{d\delta} = \frac{\left(1 - \frac{v}{d}\right)\csc^2\delta}{1 + \left[\frac{h}{d} + \left(1 - \frac{v}{d}\right)\cot\delta\right]^2} - 1 \qquad (12)$$

Position distortion is greatest when $d\eta/\delta = 0$. (12) then becomes

$$v\left(1 - \frac{v}{d}\right)\cot^2\delta - 2h\left(1 - \frac{v}{d}\right)\cot\delta = \frac{h^2}{d} + v \qquad (13)$$

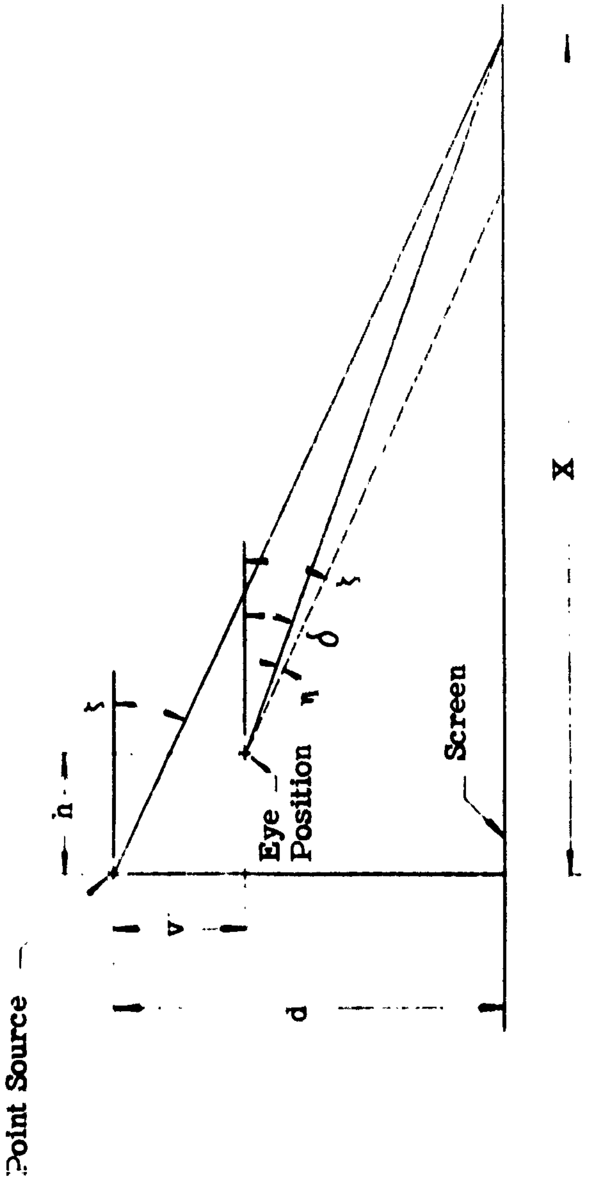


Figure I - 2 - Schematic Diagram Showing Position Distortion on a Flat Horizontal Screen Resulting From Displacement of the Eye From the Point Source.

For the case where the point source is directly above the eye, h = 0; (13) becomes

$$\delta = \cot^{-1} \sqrt{\frac{d}{d - v}} \tag{14}$$

And (11) becomes

$$\eta = \cot^{-1} \left(1 - \frac{v}{d}\right) \sqrt{\frac{d}{d - v}} - \cot^{-1} \sqrt{\frac{d}{d - v}} \tag{15}$$

<u>I - 3</u> Position Distortion on a Circular Screen with its Center at the Point Source

By definition, position distortion, η , is

$$\eta = \zeta - \delta \quad \text{Hence when } \zeta = \delta \;,\; \eta = 0 \tag{1}$$

In figure I - 3, let

$$Y = d \sin \zeta \tag{16}$$

$$X = d \cos \zeta \tag{17}$$

$$\delta = \tan^{-1} \left(\frac{Y - v}{X - h} \right) \text{ or } \tan \delta = \frac{Y - v}{X - h} \tag{18}$$

Substitute (16) and (17) in (18)

$$\tan \delta = \frac{d \sin \zeta - v}{d \cos \zeta - h} \tag{19}$$

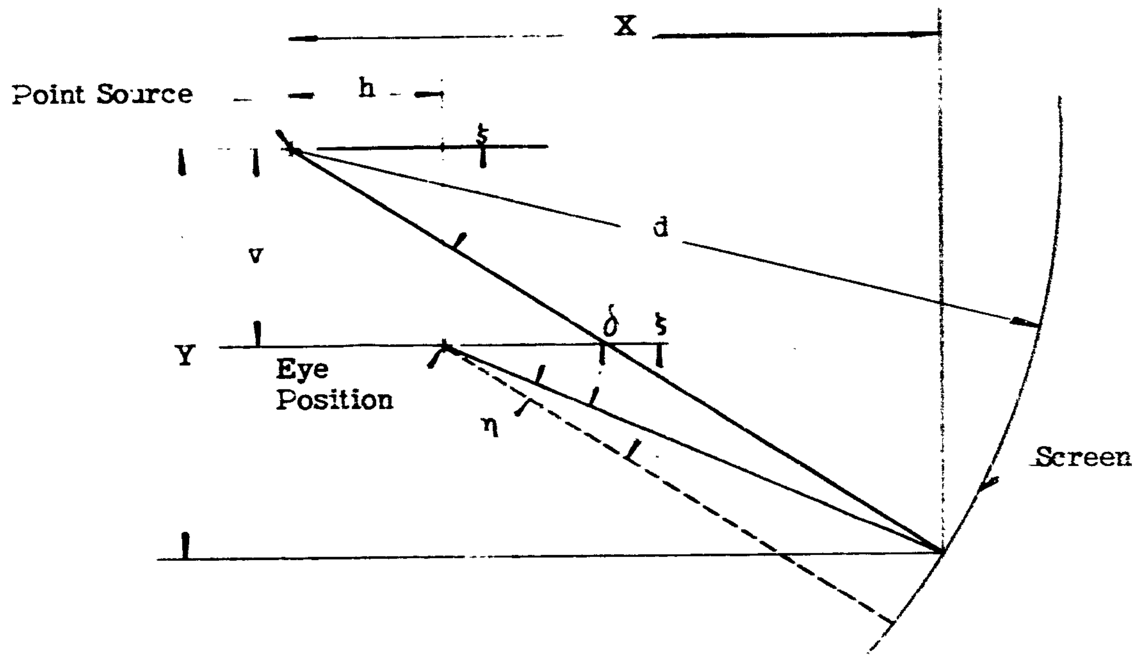


Figure I-3 - Schematic Diagram Showing Position Distortion on Circular Screen Centered at the Point Source Resulting From Displacement of the Eye From the Point Source.

From trigonometry

$$\tan \delta = \frac{\sin \delta}{\cos \delta} \tag{20}$$

Substitute (20) in (19) and simplify

$$\sin \zeta \ \cos \delta \ - \cos \zeta \ \sin \delta = \frac{v \cos \delta \ - h \sin \delta}{d} \tag{21}$$

From trigonometry

$$\sin \zeta \ \cos \delta \ - \cos \zeta \ \sin \delta = \sin (\zeta - \delta) \tag{22}$$

And from (1)

$$\sin \eta = \sin (\zeta - \delta) \tag{23}$$

Substitute (22) and (23) in (21)

$$\eta = \sin^{-1} \left[\frac{v}{d} \cos \delta - \frac{h}{d} \sin \delta \right] \tag{24}$$

Let

$$X' = \frac{v}{d} \cos \delta - \frac{h}{d} \sin \delta \tag{25}$$

Substitute (25) in (24) and differentiate with respect to δ

$$\frac{d \eta}{d \delta} = \frac{d (\sin^{-1} X')}{d \delta}$$

But

$$\frac{d\,(\sin^{-1} X')}{d\,\delta} = \frac{1}{\sqrt{1 - X'^2}} \quad \frac{d\,X'}{d\,\delta}$$

And

$$\frac{d\,X'}{d\,\delta} = \frac{v}{d}\,(-\sin\delta\,) - \frac{h}{d}\,(\cos\delta\,)$$

Therefore

$$\frac{d\,\eta}{d\,\delta} = -\frac{\frac{v}{d}\sin\delta + \frac{h}{d}\cos\delta}{\sqrt{1 - (\frac{v}{d}\cos\delta - \frac{h}{d}\sin\delta)^2}}$$

$$\frac{d\,\eta}{d\,\delta} = -\frac{v\sin\delta + h\cos\delta}{\sqrt{d^2 - (v\cos\delta - h\sin\delta)^2}} \tag{26}$$

Position distortion is a maximum when $d\eta/d\delta = 0$; (26) then becomes

$$-\frac{v\sin\delta + h\cos\delta}{\sqrt{d^2 - (v\cos\delta - h\sin\delta)^2}} = 0$$

$$-v\sin\delta - h\cos\delta = 0$$

$$v\sin\delta = -h\cos\delta$$

$$\frac{\sin\delta}{\cos\delta} = \tan\delta = -\frac{h}{v} \tag{27}$$

For the case where the point source is directly above the eye of the observer, h = 0; (27) becomes

$$\delta = \tan^{-1} 0 = 0$$

And (24) becomes

$$\eta = \sin^{-1}\left(\frac{v}{d}\right)$$

I - 4 Size Distortion on All Screen Shapes

In figure I - 4, an object viewed from the point source (a viewing position free from distortion) subtends an angle at the eye

$$\Delta\zeta = \zeta_2 - \zeta_1 \qquad (28)$$

When viewed from a position distant v below the point source and distant h in front of the point source, the same object subtends an angle at the eye

$$\Delta\delta = \delta_2 - \delta_1 \qquad (29)$$

Size distortion, $\Delta\eta$, is defined as

$$\Delta\eta = \Delta\zeta - \Delta\delta \qquad (30)$$

Substitute (28) and (29) in (30)

$$\Delta\eta = (\zeta_2 - \zeta_1) - (\delta_2 - \delta_1)$$

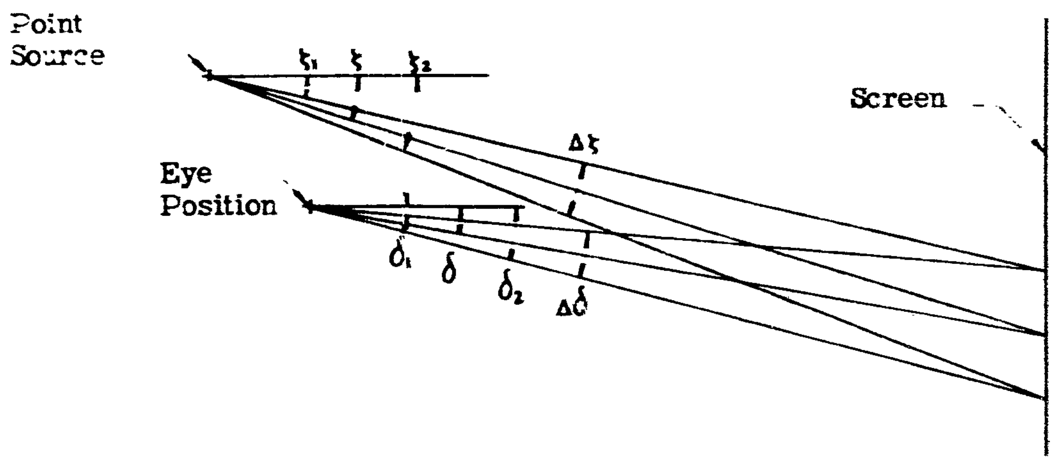


Figure I-4 - Schematic Diagram Showing Size Distortion on a Flat Vertical Screen Resulting From Displacement of the Eye From the Point Source.

$$\Delta\eta = (\zeta_2 - \delta_2) - (\zeta_1 - \delta_1)$$

But, by definition,

$$\eta_2 = \zeta_2 - \delta_2 \tag{1a}$$

$$\eta_1 = \zeta_1 - \delta_1 \tag{1b}$$

Therefore

$$\Delta\eta = \eta_2 - \eta_1 \tag{31}$$

Differentiate (31) with respect to δ

$$\frac{d\Delta\eta}{d\delta} = \frac{d(\eta_2 - \eta_1)}{d\delta}$$

$$\frac{d\Delta\eta}{d\delta} = \frac{d\eta_2}{d\delta} - \frac{d\eta_1}{d\delta} \tag{32}$$

I - 5 Position Distortion on a Circular Screen with its Center at the Eye of Observer Using Rear Screen Projection System

By definition

$$\eta = \zeta - \delta \qquad \text{Hence when } \zeta = \delta, \ \eta = 0 \tag{1}$$

In figure I - 5, let

$$Y = d \sin \delta \tag{33}$$

$$X = d \cos \delta \tag{34}$$

Then

$$\zeta = \tan^{-1} \frac{Y}{2d - X} \tag{35}$$

Substitute (33) and (34) in (35)

$$\zeta = \tan^{-1} \left[\frac{\sin \delta}{2 - \cos \delta} \right] \tag{36}$$

Substitute (36) in (1)

$$\eta = \tan^{-1} \left[\frac{\sin \delta}{2 - \cos \delta} \right] - \delta \tag{37}$$

Let

$$X' = \frac{\sin \delta}{2 - \cos \delta} \tag{38}$$

Substitute (38) in (37) and differentiate with respect to δ

$$\frac{d\eta}{d\delta} = \frac{d(\tan^{-1} X')}{d\delta} - 1$$

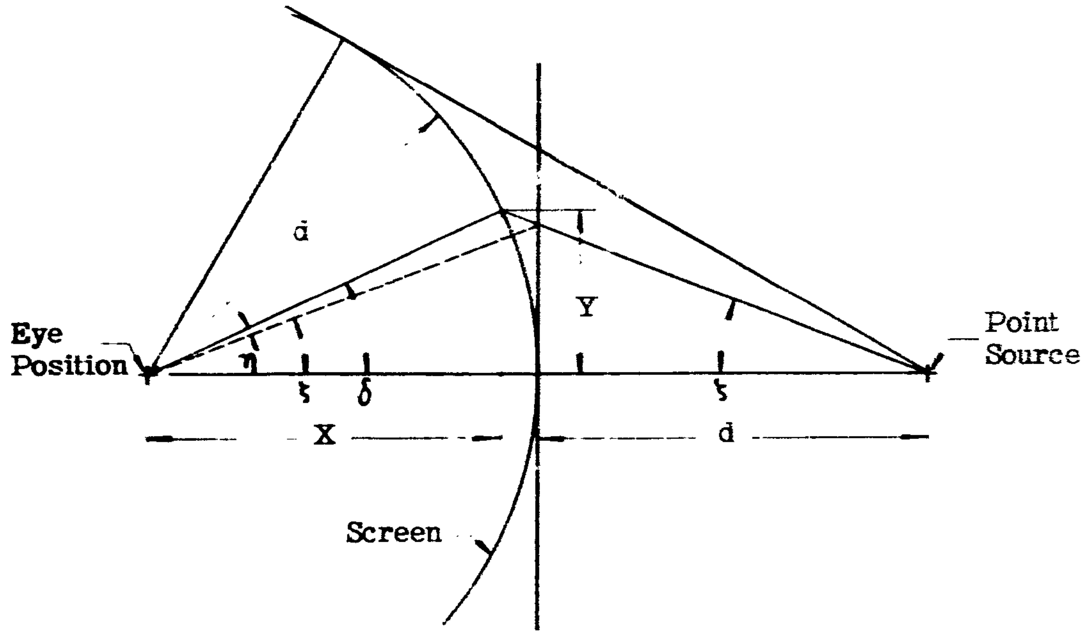


Figure I-5 - Schematic Diagram Showing Position Distortion on a Circular Screen Centered at the Eye When Using the Rear Screen Projection System.

But

$$\frac{d\,(\tan^{-1} X')}{d\,\delta} = \frac{1}{1 + X'^2} \quad \frac{d\,X'}{d\,\delta}$$

And

$$\frac{d\,X'}{d\,\delta} = \frac{(2 - \cos\delta)(\cos\delta) - (\sin\delta)(\sin\delta)}{(2 - \cos\delta)^2}$$

Therefore

$$\frac{d\,\eta}{d\,\delta} = \frac{2\cos\delta - 1}{(2 - \cos\delta)^2} - 1 \qquad (39)$$

Position distortion is a minimum when $d\eta/d\delta = 0$; then (39) becomes

$$\delta = \cos^{-1} 1 = 0 \qquad (40)$$

And (37) becomes

$$\eta = 0 \qquad (41)$$

APPENDIX II

Derivation of Resolution Equations

<u>II - 1</u> <u>Derivation of an Expression for Distortion of the Display-Image Width due to the Use of an Extended Source Rather than a Geometric Point Source</u>

In figure II - 1, let

$$X = (D - D')/2 \quad \text{or} \quad D = D' + 2X \tag{42}$$

By definition

$$M = (a + b)/a \quad \text{or} \quad b = a(M - 1) \tag{43}$$

$$M = D'/J \quad \text{or} \quad D' = JM \tag{44}$$

$$P' = D/D' \tag{45}$$

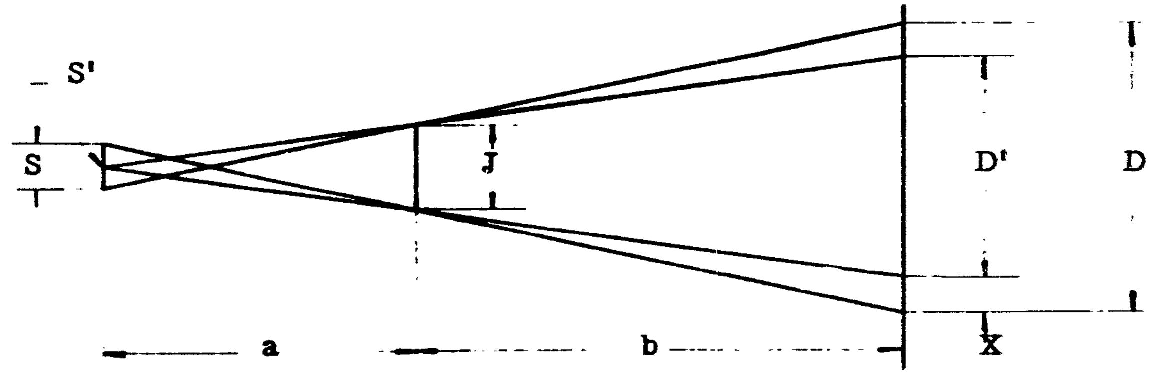
$$P_1 = S/J \tag{46}$$

Substitute (42) in (45)

$$P' = (D' + 2X)/D' \tag{47}$$

By similar triangles in figure II - 1

$$\frac{S/2}{a} = \frac{X}{b} \quad \text{or} \quad X = \frac{Sb}{2a} \tag{48}$$



F. . ; II - 1 - Schematic Diagram Showing Width of the Images Formed by Projection of opaque Line of Width, J, by Extended Source, S, and by Geometric Point Source, S'.

Substitute (43), (44) and (48) in (47)

$$P' = \frac{JM \quad S(M - 1)}{JM}$$

$$P' = 1 + \frac{S}{J}\left(\frac{M - 1}{M}\right) \tag{49}$$

Substitute (46) in (49)

$$P' = 1 + P_1\left(\frac{M - 1}{M}\right) \tag{50}$$

II - 2 Derivation of an Expression for the Quality of Resolution and Definition as Affected by Magnification and the Source Size to Display-Object Line Width Ratio

In figure II - 2, let

$$X = (D - D')/2 \quad \text{or} \quad D = D' + 2X \tag{51}$$

By definition

$$M = (a + b)/a \quad \text{or} \quad b = a(M - 1) \tag{52}$$

$$M = D'/J \quad \text{or} \quad D' = JM \tag{53}$$

$$D = U + 2G \tag{54}$$

$$P'' = U/D \tag{55}$$

$$P_1 = S/J \tag{56}$$

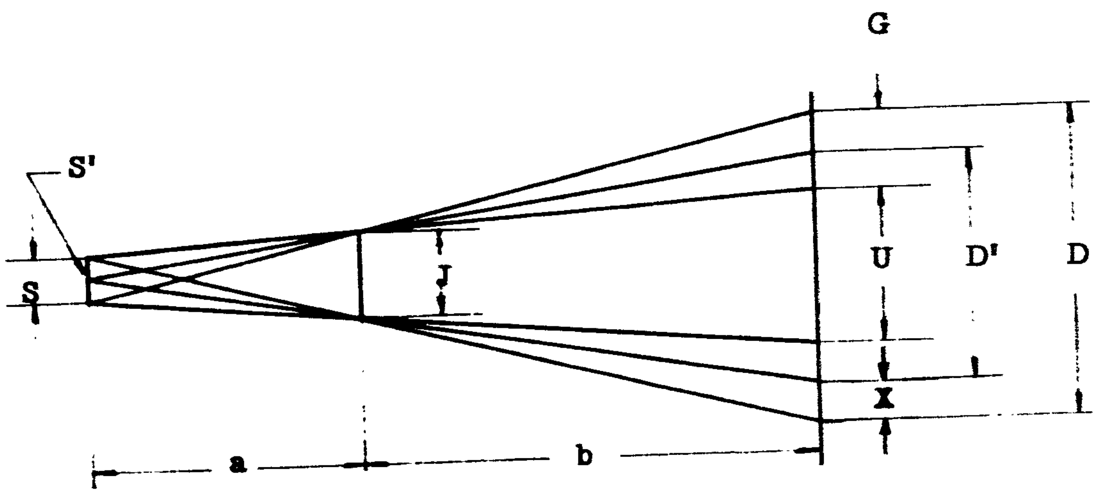


Figure II - 2 - Schematic Diagram Showing Characteristics of the Images Formed by Projection of opaque Line of Width, J, by Extended Source, S, and by Geometric Point Source, S'.

By similar triangles from figure II - 2

$$S/a = G/b \qquad \text{or} \qquad G = Sb/a \tag{57}$$

Similarly

$$\frac{S/2}{a} = \frac{X}{b} \qquad \text{or} \qquad X = \frac{Sb}{2a} \tag{58}$$

Substitute (57) in (58)

$$X = G/2 \tag{59}$$

Substitute (51) and (59) in (54)

$$D' + 2X = U + 4X \qquad \text{or} \qquad U = D' - 2X \tag{60}$$

Substitute (51) and (60) in (55)

$$P'' = \frac{D' - 2X}{D' + 2X} \tag{61}$$

Substitute (53) and (58) in (61)

$$P'' = \frac{JM - \frac{Sb}{a}}{JM + \frac{Sb}{a}} \tag{62}$$

Substitute (52) in (62)

$$P'' = \frac{JM - S(M - 1)}{JM + S(M - 1)}$$

$$P'' = \frac{M - \frac{S}{J}(M - 1)}{M + \frac{S}{J}(M - 1)}$$

Substitute for S/J for (56)

$$P'' = \frac{M - P_1 (M - 1)}{M + P_1 (M - 1)}$$

$$P'' = \frac{1 - P_1\left(\frac{M - 1}{M}\right)}{1 + P_1\left(\frac{M - 1}{M}\right)} \qquad (63)$$

II - 3 Derivation of an Expression for Display-Image Quality as Affected by Extended Source Size and by Distance from Source to Display-Object

Consider a line of demarcation between a red and a green area on display-object projected by an extended "point" source, S, distant, a, from the display-object as shown in figure II-3. A display-image is formed by this projection system on a screen distant, b, from the display-object. This display-image will consist of a red area and a green area separated by an area of demarcation which will be a combination of red and green of width, X. The edges of this area of demarcation will subtend an angle, α, in space with its vertex at the line of demarcation on the display-object and will subtend an angle, β, in space with its vertex at the eye of the observer. The angle, α, subtended by X at the display-object is equal to the angle subtended by the extended source, S, at the same point. If the eye of the

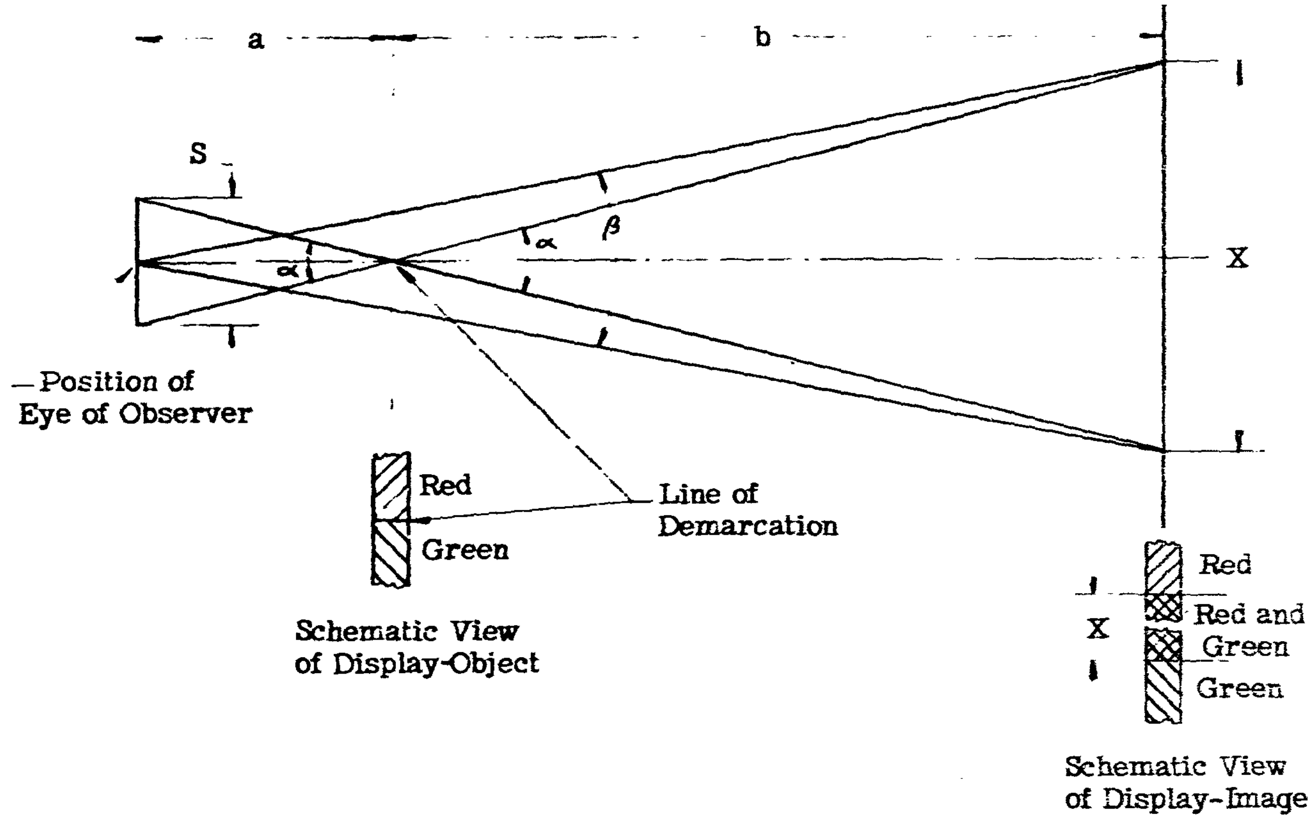


Figure II-3 - Schematic Diagram Showing the Angle, α, Subtended at a Line of Demarcation on a Display-Object by an Extended Source, S, and the Angle, β, Subtended at the Eye of the Observer by the Display-Image Formed by that Line and Extended Source, S.

observer is placed to coincide with the center of the extended source, S, the following relationships hold. (In practice, the eye is held as close to the point source as possible.)

From figure II - 3

$$\tan \frac{\alpha}{2} = \frac{S}{2a} = \frac{X}{2b} \tag{64}$$

$$\tan \frac{\beta}{2} = \frac{X}{2(a+b)} \tag{65}$$

If a is small compared to b

$$a + b \approx b \tag{66}$$

Then

$$\frac{X}{2(a+b)} \approx \frac{X}{2b} \tag{67}$$

Substitute this in (65) and then (64) and (65) become

$$\tan \frac{\alpha}{2} \approx \tan \frac{\beta}{2} \tag{68}$$

And

$$\alpha \approx \beta \tag{69}$$

Then

$$\tan \frac{\beta}{2} \approx \frac{S}{2a} \tag{70}$$

From trigonometry

$$\tan \alpha = \frac{2 \tan \frac{\alpha}{2}}{1 - \tan^2 \frac{\alpha}{2}} \tag{71}$$

But if $\alpha/2$ is very small then in (71)

$$1 - \tan^2 \frac{\alpha}{2} \longrightarrow 1 \tag{72}$$

And (71) becomes

$$2 \tan \frac{\alpha}{2} \approx \tan \alpha \tag{73}$$

Then from (68), (70) and (73)

$$\tan \beta \approx \tan \alpha \approx \frac{S}{a} \tag{74}$$

It can easily be shown that for $\beta \leq 1^{\circ}$ (and $\alpha \leq 1^{\circ}$) these approximations are very close. While the eye will readily distinguish an area of demarcation which subtends an angle $\beta > 1^{\circ}$, the ability of the eye to distinguish an area of demarcation falls off rapidly as the angle subtended, β, falls below 1°.

APPENDIX III

Interaction of Diffraction and Extended Source Effects as Display-Object Line Width and its Distance from the Extended Source Vary

From the laws of diffraction

$$\sin \gamma = \frac{\lambda}{J} \qquad (75)$$

From figure III - 1

$$\tan \frac{\alpha}{2} = \frac{S}{2a} \qquad (76)$$

When γ is very small, $\sin\gamma \approx \gamma$ in radians and (75) becomes

$$\gamma \approx \frac{\lambda}{J} \qquad (77)$$

When α is small, $2 \tan\alpha/2 \approx \tan\alpha \approx \alpha$ in radians and (76) becomes

$$\alpha \approx \frac{S}{a}$$

If $J = S$ this may be written

$$\alpha \approx \frac{J}{a} \qquad (78)$$

If $\alpha = \gamma$ in radians then from (77) and (78)

$$\frac{\lambda}{J} \approx \frac{J}{a}$$

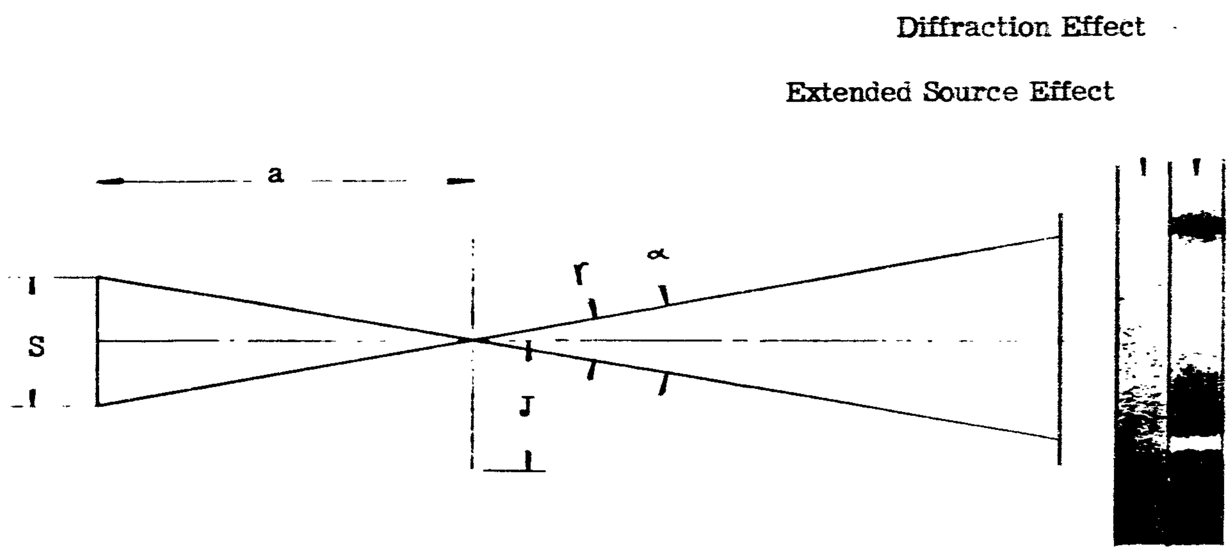


Figure III-1 - Schematic Diagram Showing the Effects of Diffraction and of Extended Source on the Display-Image.

Or

$$a \approx \frac{J^2}{\lambda}$$

Substitute in this the value of J from (77)

$$a \approx \frac{\lambda}{\gamma^2} \qquad (79)$$

APPENDIX IV

TABULATION OF POINT SOURCE LAMPS

Name	Make	Type	Power Watts
Osram HBO-107*	Osram-German	MV	100 most eff.
Osram XBO-162	Osram-German	XV	160
Concentrated Arc C-25W (Zirconium)	Sylvania	CA	25
Concentrated Arc 2W (Zirconium)	Sylvania	CA	2
Concentrated Arc DC 300W (Zirconium)	Sylvania	CA	300
A-25 Hafnium 10W Cathode	Sylvania	CA	25
A-10 Hafnium	Sylvania	CA	10
Pointolite 30 CP	Biddle	T	20-ballast power
Pointolite 100 CP	Biddle	T	60-ballast power
Pointolite 150 CP	Biddle	T	100

NOTE:
XV xenon vapor
MV mercury vapor
CA concentrated arc
T tungsten
L length
D diameter

* The Osram HBO-109 is identical to the Osram HBO-107 except that HBO-107 has a starting electrode and HBO-109 does not.

TABULATION OF POINT SOURCE LAMPS (Cont'd)

Name	Table of Brightness (cd/in²) *	Source Distance from envelope (in.)	Temp °K
Osram HBO-107	620,000	.225"	
Osram XBO-162	58,000	.375	
Concentrated Arc C-25W (Zirconium)	15,000	.453	3200
Concentrated Arc 2W (Zirconium)	46,000	.25	3200
Concentrated Arc DC 300W (Zirconium)	23,800	1-5/8	3200
A-25 Hafnium 10W Cathode	81,000 Exp.	.453 in. max.	3300
A-10 Hafnium		.453 in. max.	3300
Pointolite 30 CP	4,450	.63	2700
Pointolite 100 CP	8,600	1.26	2700
Pointolite 150 CP	8,700	1.45	2700

* Candles per square inch

TABULATION OF POINT SOURCE LAMPS (Cont'd)

Name	Over-all Size (in.)	Table Values Intensity-Candles	Table Arc Dimensions (in.)
Osram HBO-107	L 3.03 D .473	150	.0118 x .0118
Osram XBO-162	L 5-7/8 D .75	260	L .069 W .035
Concentrated Arc C-25W (Zirconium)	L 3-11/16 D 1-1/8	10.5	D .0287
Concentrated Arc 2W (Zirconium)	L 2-1/16 D 9/16	.33	D .003
Concentrated Arc DC 300W(Zirconium)	L 7-7/32 D 3-1/4	250	D .115
A-25 Hafnium 10W	L 3-11/16 D 1-1/8	9.6	.014) .008) 2 lamps
A-10 Hafnium	L 3-11/16 D 1-1/8	3.3	.007) .009) 2 lamps
Pointolite 30 CP	L 2 D 1.25	30	.075
Pointolite 100 CP	L 3	100	.1
Pointolite 150 CP	L 3	150	095

TABULATION OF POINT SOURCE LAMPS (Cont'd)

Name	App. Coverage Angle of Light	Temp. of Lamp (°C)	Lamp Pressure "Atmospheres"
Osram HBO-107	240+	Bulb 400 (app.)	35-70
Osram XBO-162	360		
Concentrated Arc C-25W (Zirconium)	150°	Bulb 179 Base 62.7	.166-
Concentrated Arc 2W (Zirconium)	90°	Bulb 60 Base 37.7	.003-
Concentrated Arc DC 300W (Zirconium)	150°+	Bulb 271 Base 82.2	.43-
A-25 Hafnium 10W Cathode	150°+	Bulb 179 Base 62.7	.166-
A-10 Hafnium	150°+	Bulb 179 Base 62.7	.166-
Pointolite 30 CP	240°+	up to 160	.333-
Pointolite 100 CP	240°+	160	.333-
Pointolite 150 CP	240°+	160	.333-

APPENDIX V

Negative Meniscus Lenses

V-1 Introduction

V-1.1 This appendix presents studies of the effects of the variables involved in the design of a lens system utilizing the negative meniscus lens on the requirements of the ideal point source. These requirements discussed in Chapter 3 (paragraph 3.2) of this report may be summarized as follows:

a) Minimum diameter

b) Maximum luminous intensity

c) Maximum angle of light output

d) Satisfactory Spectral Distribution

e) Minimum envelope

f) Envelope free from striations

g) Envelope at or near room temperature

h) Safety

i) Maximum life

j) Reasonable cost

V-1.2 A lens having the centers of curvature of both refracting surfaces on the same side is called a meniscus lens. When, in addition, a meniscus lens is thicker at the periphery than at the center, it is termed negative.

V-1.3 A negative meniscus lens collects diverging rays of light emitted by a finite "point" source such as the Osram HBO-109 lamp. If the distances between the center of the lamp and the centers of curvature of the lens are made to obey requirements derived in this Appendix, effective size reduction and a further divergence of the light is achieved. Being a negative lens, it creates a virtual image of the point source (object). Using this virtual image as the object of a second lens, further size reduction can be obtained. However, each successive lens, receives only a small cone of the luminous flux emitted by the previous lens and the

luminous flux transmitted by the lens system is thereby reduced.

V-1.4 The variables involved in the design of such a lens system are: the optical glass (including its index of refraction), the radius of the lens surfaces, the minimum lens thickness and the position of the "point" source (object) with respect to the lens.

V-2 The Aplanatic Negative Meniscus Lens.

V-2.1 Introduction to Theory

V-2.2 In sections V-2.6 and V-2.7, it is shown that if a point source of light serving as the object of a negative meniscus lens is located at a distance $R_1 + n_2 R_1$ from the first surface of the lens when the first surface has a radius of curvature, R_1, and the lens has an index of refraction, n_2, then the lens will form a virtual image of the point source at a distance $R_1 + (R_1/n_2) + t$ from the second surface of the lens when the second surface has a radius of curvature, $R_2 = R_1 + (R_1 n_2) + t$ (equations 83, 88, 90, 92 and 94). It is further shown that this virtual image is smaller than the real point source object by a factor of $1/n_2$ (equation 99).

V-2.3 In sections V-2.8 and V-2.9, it is shown that the maximum half-angle of light output, ϕ', is $\sin^{-1} (n_2 / \sqrt{n_2^2 + 1})$ (equation 104). In addition, it is shown that, neglecting light losses in the lens due to reflection and absorption, the brightness of this image, B', is equal to the brightness of the object, B, (equation 107) and the luminous intensity of this image, I', is less than that of the object, I, by a factor of $\sqrt{n_2^2 + 1} - 1 / \sqrt{n_2^2 + 1} - n_2$ (equation 111).

V-2.4 In section V-2.10, aberrations of this lens are discussed and it is shown that this lens is aplanatic (by definition, free from spherical aberration and coma).

V-2.5 In section V-2.29, the parameters of a specific aplanatic negative meniscus lens are calculated and, in section V-2.34, the theoretical and experimental characteristics of this lens are examined with particular attention to their relationship to requirements for the point source system.

V-2.6 Development of expressions for the object distance and the image distance

Consider that rays from a point source of light are incident on a negative meniscus lens having an index of refraction, n_2, and a radius of curvature of the first surface, R_1, located in air ($n_1 = 1$) as shown in figure V-1. Then Snell's Law may be written

$$\sin i_1 = n_2 \sin r_1 \tag{80}$$

Consider triangle ACD in figure V-1; by the law of sines

$$\frac{\sin \theta_1}{R_1} = \frac{\sin i_1}{s_1 - R_1} \tag{81}$$

Recalling that, by convention, θ_1 and s_1 are positive and i_1 and R_1 are negative, make this explicit for the first surface:

$$\frac{\sin \theta_1}{-R_1} = \frac{\sin(-i_1)}{s_1 + R_1} = \frac{-\sin i_1}{s_1 + R_1} \tag{81a}$$

Substitute (80), where $i_1 = -i_1$ and $r_1 = -r_1$, in (81a)

$$\frac{\sin \theta_1}{-R_1} = \frac{-n_2 \sin r_1}{s_1 + R_1} \tag{82}$$

Let

$$s_1 + R_1 = -R_1 n_2$$

then

$$s_1 = -(R_1 + R_1 n_2) \tag{83}$$

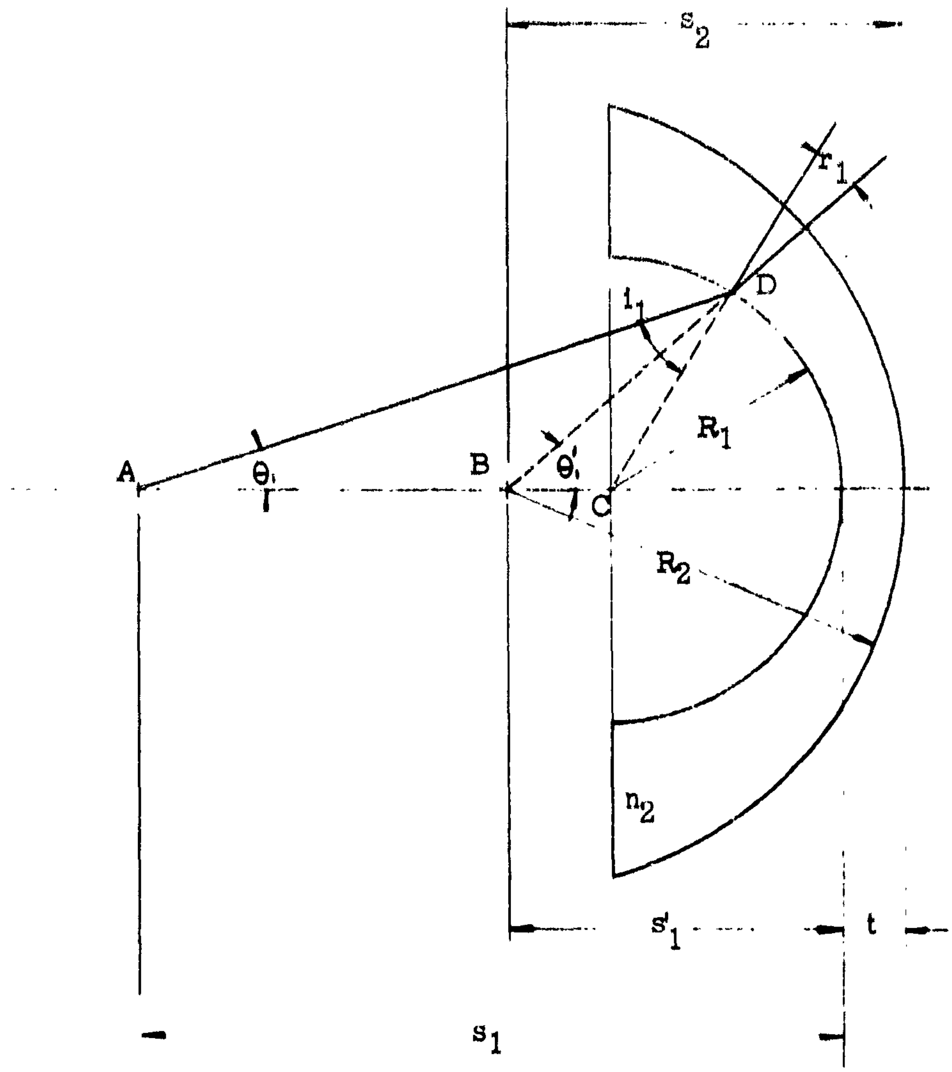


Figure V-1 - Ray Tracing Diagram of Aplanatic Negative Meniscus Lens.

Substitute this in (82)

$$\frac{\sin \theta_1}{-R_1} = \frac{-n_2 \sin r_1}{-R_1 n_2}$$

$$\sin \theta_1 = -\sin r_1$$

$$\theta_1 = -r_1 \tag{84}$$

Consider triangle ABD in figure V-1; the sum of the angles equals π radians:

$$\theta_1 + i_1 - r_1 + \pi - \theta_1' = \pi \tag{85}$$

Recalling that, by convention, θ_1 and θ_1' are positive and i_1 and r_1 are negative, make this explicit for the first surface and simplify:

$$\theta_1 - i_1 + r_1 - \theta_1' = 0 \tag{85a}$$

Substitute (84) in this

$$\theta_1' = -i_1$$

$$\sin\theta_1' = -\sin i_1 \tag{86}$$

Consider triangle BCD in figure V-1; by the law of sines

$$\frac{\sin \theta_1'}{R_1} = \frac{\sin r_1}{s_1' - R_1} \tag{87}$$

Recalling that, by convention, θ_1' is positive and r_1, s_1' and R_1 are negative, make this explicit for the first surface:

$$\frac{\sin \theta_1'}{-R_1} = \frac{-\sin r_1}{-s_1' + R_1} \tag{87a}$$

Substitute (86) in this:

$$\frac{-\sin i_1}{-R_1} = \frac{-\sin r_1}{-s_1' + R_1}$$

Substitute (80) in this and simplify

$$\frac{-n_2}{-R_1} = \frac{-1}{-s_1' + R_1}$$

Solve for s_1'

$$s_1' = R_1 + \frac{R_1}{n_2} \tag{88}$$

Consider that the second surface of this lens has a radius, R_2. Then recalling that, by convention, θ_2 and s_2 are positive and i_2 and R_2 are negative, make (81) explicit for the second surface:

$$\frac{\sin \theta_2}{-R_2} = \frac{-\sin i_2}{s_2 + R_2}$$

Solving for s_2

$$s_2 = -R_2 + R_2 \frac{\sin i_2}{\sin\theta_2} \tag{89}$$

Select the radius of the second surface so that the angle of incidence, i_2, of rays incident on this surface from the point image formed by the first surface is normal to the surface:

$$-(s_1' + t) = s_2 \tag{90}$$

$$i_2 = 0 \tag{91}$$

$$\sin i_2 = 0$$

Substitute this in (89)

$$s_2 = -R_2 \tag{92}$$

Recalling that, by convention, θ_2' is positive and r_2, s_2' and R_2 are negative, make (87) explicit for the second surface:

$$\frac{\sin\theta_2'}{-R_2} = \frac{-\sin r_2}{s_2' + R_2}$$

Solving for s_2'

$$s_2' = R_2 - R_2 \frac{\sin r_2}{\sin\theta_2'} \tag{93}$$

For the second surface Snell's Law may be written

$$n_2 \sin i_2 = \sin r_2 \tag{80a}$$

But from (91), $\sin i_2 = 0$, therefore

$$\sin r_2 = 0$$

Substitute this in (93):

$$s_2' = R_2 \tag{94}$$

V-2.7 Development of expressions for magnification.

From Abbe's Sine Condition, the magnification of the object by the first surface, m_1, is

$$m_1 = \frac{\sin\theta_1}{n_2 \sin\theta_1'} \tag{95}$$

Substitute (84) and (86) in (95)

$$m_1 = \frac{-\sin r_1}{-n_2 \sin i_1}$$

Substitute (80) in this:

$$m_1 = \frac{1}{n_2^2} \tag{96}$$

From Abbe's Sine Condition, the magnification of the object of the second surface, m_2, is

$$m_2 = \frac{n_2 \sin\theta_2}{\sin\theta_2'} \tag{97}$$

Make (85) explicit for the second surface where $i_2 = 0$ and $r_2 = 0$:

$$\theta_2 + \pi - \theta_2' = \pi$$

$$\theta_2 = \theta_2'$$

Substitute this in (97)

$$m_2 = n_2 \tag{98}$$

The lateral magnification of a lens, m_L, is the product of the magnifications of the surfaces:

$$m_L = m_1 m_2 = \frac{1}{n_2} \tag{99}$$

By definition, the longitudinal magnification, Γ_L, is

$$\Gamma_L = -(m_L)^2 = -\frac{1}{n_2^2} \tag{100}$$

V-2.8 Development of expressions comparing the luminance of the image with that of the object

Under optimum conditions (no light losses in the lens from reflection and absorption), the luminous flux incident on the lens, F, is all transmitted by the lens. Then the luminous flux transmitted, F', is equal to F. When ϕ is the limiting value of the slope angle, θ, for a radius of aperture, R_1, as shown in figure V-2, Lambert's Cosine Law may be written

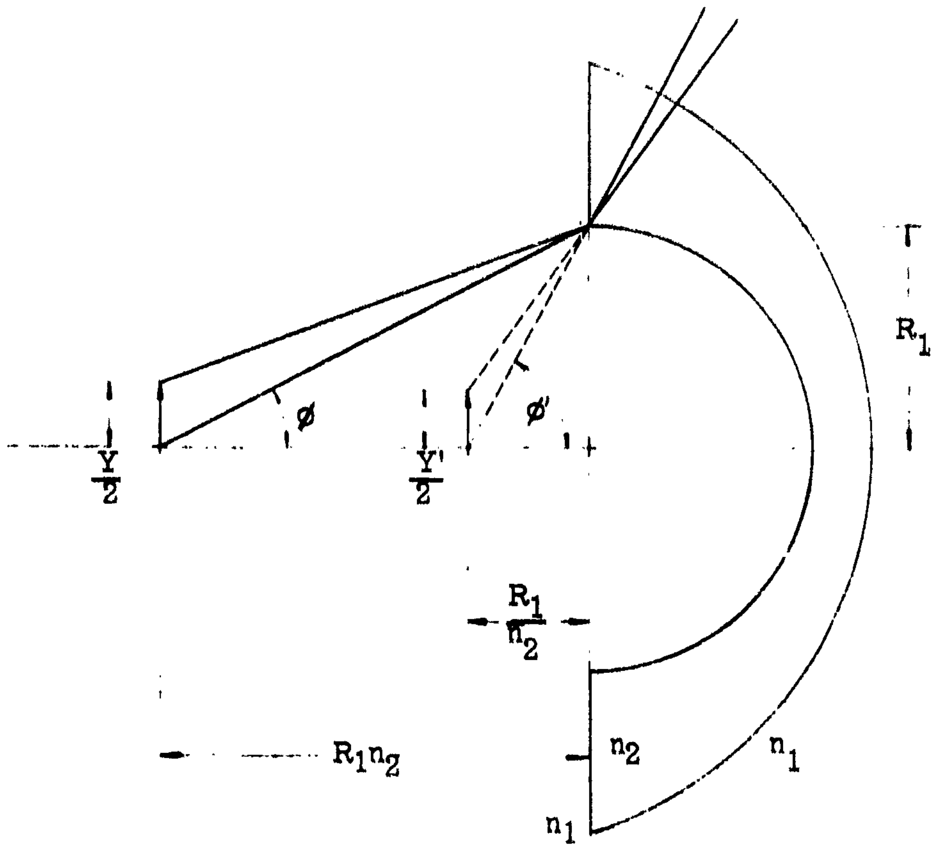


Figure V - 2 - Diagram of Image Formation by the Aplanatic Negative Meniscus Lens.

$$F = 2\pi B\, Y_1 \int_0^{\phi} \sin\theta \cos\theta \, d\theta \tag{101}$$

Integrate this

$$F = \pi\, B\, Y_1 \sin^2 \phi$$

Similiarly on the image side

$$F' = \pi\, B'\, Y_1' \sin^2 \phi'$$

Where Y_1 and Y_1' are the area of the object and the image respectively, and ϕ' is the limiting value of θ' when ϕ is the limiting value of θ .

Since $F = F'$, then

$$B\, Y_1 \sin^2 \phi = B' Y_1' \sin^2 \phi'$$

$$\frac{B}{B'} = \frac{Y_1' \sin^2 \phi'}{Y_1 \sin^2 \phi} \tag{102}$$

From figure V-2

$$\sin \phi = \frac{R_1}{\pm\sqrt{R_1^2 + R_1^2 n_2^2}} = \frac{1}{\pm\sqrt{1 + n_2^2}} \tag{103}$$

$$\sin \phi' \quad \frac{R_1}{\pm\sqrt{R_1^2 + R_1^2/n_2^2}} = \frac{1}{\pm\sqrt{1 + 1/n_2^2}} \tag{104}$$

Divide $\sin \phi'$ by $\sin \phi$:

$$\frac{\sin \phi'}{\sin \phi} = \pm \sqrt{\frac{1 + n_2^2}{\frac{n_2^2 + 1}{n_2^2}}} = \pm n_2 \qquad (105)$$

Also from figure V-2, the area of the object of radius Y/2 is

$$Y_1 = \pi (Y/2)^2$$

Similarly the area of the image of radius Y'/2 is

$$Y_1' = \pi (Y'/2)^2$$

Therefore

$$\frac{Y_1'}{Y_1} = \frac{Y'^2}{Y^2}$$

But, by definition, and (99)

$$m_L = \frac{Y'}{Y} = \frac{1}{n_2} \qquad (106)$$

Substitute (106) and (105) in (102):

$$\frac{B}{B'} = \frac{1}{n_2^2} n_2^2 = 1 \qquad (107)$$

<u>V-2.9</u> Development of expressions comparing the luminous intensity of the image with that of the object.

By definition, the luminous intensity, I, is total luminous flux within a small solid angle, ω, when the total flux radiated is F. Since the flux radiated by the Osram HBO-109 lamp is uniform through a very wide angle, when this lamp is properly oriented relative to the negative meniscus lens,

$$F = I\omega \tag{107}$$

where ω is the solid angle of flux in steradians incident on the lens as shown in figure V-3. ω equals the area of the spherical surface $\overline{DFE}$ divided by the square of its radius $\overline{AD}$:

$$\omega = \frac{2\pi XY}{X^2} = \frac{2\pi Y}{X} \tag{108}$$

where

$$X = \overline{AD} = \sqrt{R_1^{\,2} + (R_1 n_2)^2}$$

$$Y = \overline{CF} = X - R_1 n_2$$

Similarly the luminous intensity, I', of the lens output is

$$F' = I'\omega'$$

where ω' is the solid angle of flux in steradians transmitted by the lens as shown in figure V-3. ω' equals the area of the spherical surface $\overline{GHJ}$ divided by the square of its radius $\overline{BG}$:

$$\omega' = \frac{2\pi X'Y'}{X'^2} = \frac{2\pi Y'}{X'} \tag{109}$$

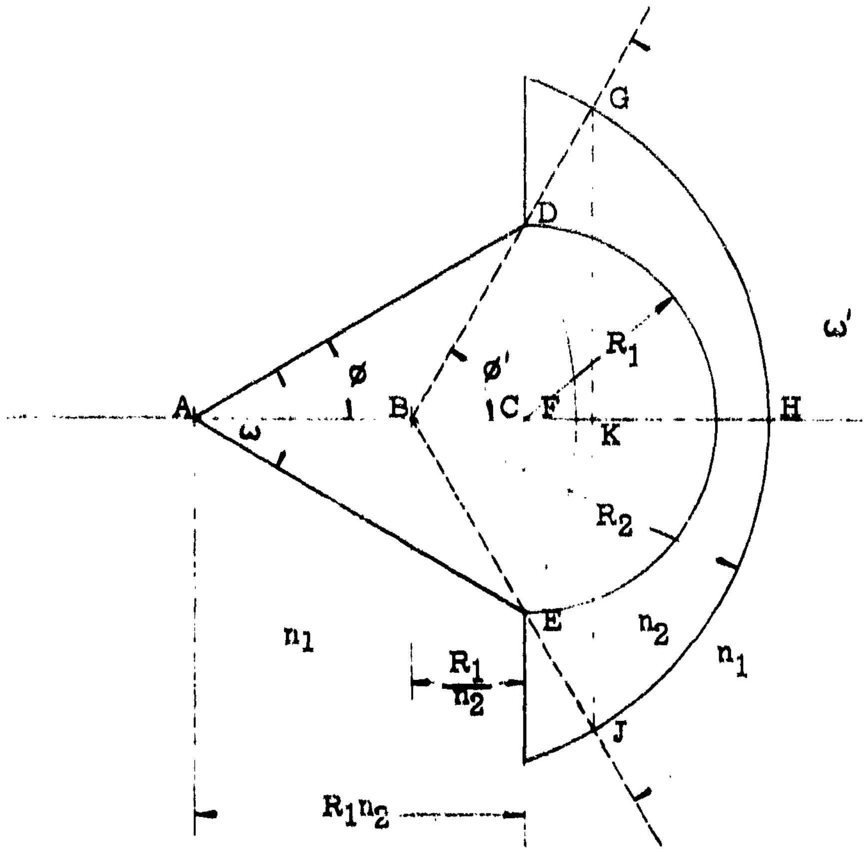


Figure V - 3 - Diagram of Aplanatic Meniscus Lens Showing Light Input and Light Output.

where

$$X' = \overline{BG} = R_2$$

$$Y' = \overline{KH} = R_2 - R_2 \cos \phi'$$

and

$$\cos \phi' = \frac{\frac{R_1}{n_2}}{\pm\sqrt{R_1^2 + \frac{R_1^2}{n_2^2}}} = \frac{1}{\pm\sqrt{1 + n_2^2}}$$

Since F = F', then

$$I \omega = I' \omega' \tag{110}$$

Substitute (108) and (109) in this and simplify

$$\frac{I}{I'} = \frac{\pm\sqrt{n_2^2 + 1} - 1}{\pm\sqrt{n_2^2 + 1} - n_2} \tag{111}$$

V-2.10 Evaluation of aberrations

V-2.11 Spherical Aberration

V-2.12 From a geometric point source on the optical axis consider that some ray travels along a path extremely close to the optical axis (paraxial) and that some other ray travels along a path at

a considerably larger angle, θ, to the optical axis. After being refracted, these rays should cross the optical axis at the same point. However, because of spherical aberration, the ray traveling along the path at angle θ will cross the optical axis before or after the paraxial ray crosses. Spherical aberration is a departure from the ideal lens condition wherein all rays from a geometric point object on the optical axis recombine to form a point image on the optical axis. Spherical aberration present in a given lens is the distance measured along the optical axis between the intercept of a ray through the lens zone in question and the intercept of the paraxial rays, and is usually expressed in terms of plus or minus percent of the focal length.

V-2.13 Usually spherical aberration cannot be eliminated from a single lens. However, by combining two lenses having spherical aberrations equal in amount but opposite in sign, it is possible to eliminate spherical aberration from a lens system.

V-2.14 Note that for the negative meniscus lens under discussion, the object distance and the image distance (equations 83, 88, 92 and 94) are independent of θ. This verifies that this negative meniscus lens is free from spherical aberration when the object distance is established according to (83) and the radius of the second surface is established according to (85) and (86).

V-2.15 Coma

V-2.16 The aberration known as coma affects rays from points not on the optical axis of a lens. It is similar to spherical aberration in that both arise from the failure of a lens to image paraxial rays and rays through outer zones at the same point. Coma differs from spherical aberration, however, in that a point object is imaged not as a circle but as a comet-shaped figure.

V-2.17 Consider again the rays discussed in paragraph V-2.12. The condition for absence of coma is that the ratio $\sin\theta_1 / \sin\theta_2'$ remain constant. Note that this ratio for the negative meniscus lens under discussion is $1/n_2$ (equation (105), a constant. Therefore, this negative meniscus lens is free from coma. Indeed, it is aplanatic as defined.

V-2.18 Chromatic aberration

V-2.19 The refractive index of all optical materials increases with the frequency of light. The displacement of an image along the

axis due to change in wavelength, is called axial or longitudinal chromatism. The variation in the size of the image is called lateral or oblique chromatism. When any lens is corrected for axial chromatic aberration, generally all that can be done is to make the lens have the same axial intercepts for two wavelengths, usually those of the C and F lines of hydrogen. In this case the other wavelengths will still focus in other planes, giving rise to a residual aberration known as secondary spectrum. One way to determine chromatic aberration is to obtain focal lengths of different wavelengths and use certain theoretical relationships. The method is very tedious and requires ray tracing.

V-2.20 Chromatic aberrations of a single lens can never be eliminated; however, they can be compensated for with the proper combination of different lens elements.

V-2.21 For the negative meniscus lens under discussion all the aberrations, with the exception of chromatic, are negligible since the object, as well as the image, are essentially point size (the smaller the object the less is the amount of aberrations). Chromatic aberrations of this lens is the limiting factor on the size of the virtual point source, assuming perfect lens curvatures. Diminishing the virtual point source further than .002" can affect the projected image by resulting in projections from two extremes of the color spectrum, thus creating a double image.

V-2.22 Astigmatism

V-2.23 A pencil of rays that fails to unite at a single image point after refraction is said to be astigmatic and the system is said to be affected with astigmatism. Although spherical aberration and coma are forms of astigmatism, the term is usually restricted to the aberration peculiar to the rays from point objects lying at a considerable distance from the axis.

V-2.24 Astigmatism and the subsequent curvature of field effect are negligible since the object and image under consideration are essentially point size and lie on or close to the optical axis.

V-2.25 Distortion

V-2.26 Deformation of the image, which is known by the descriptive term, "distortion", is caused by a variation in the magnification with the distance from the optical axis. If the magnification increases with this distance, the distortion is considered positive, if magnification decreases as this distance increases, distortion is negative. From the shape of the image of a square object, the two types of distortion are sometimes called pin cushion distortion (positive) and barrel distortion (negative).

V-2.27 The conditions for distortionless imagery are:

a) the ratio $\tan\theta_2'/\tan\theta_1$ must be constant for all values of θ_1.

b) the system must be corrected for spherical aberrations.

V-2.28 In paragraph V-2.17 it was established that for this negative meniscus lens $\sin\theta_1/\sin\theta_2'$ equals $1/n_2$, a constant (equation 105). It is easily seen then that unless θ_1 equals θ_2', the ratio of their tangents is not constant. Hence, this lens is not free from distortion. However, since the object (the point source) is very small and is located on the optical axis, the distance from the optical axis to the most remote element of the object is very small and the effects of distortion are negligible.

V-2.29 Theoretical calculations for an experimental lens.

V-2.30 Since reduction of the source diameter by an aplanatic negative meniscus lens is inversely proportional to the index of refraction of the lens material (equation 99), a material with an index of 1.88 was selected (for discussion of this material see paragraph V-4.1). In order to obtain a small envelope about the virtual source formed by the lens, small lens radii must be used. A convenient first surface radius of .125" was selected.

V-2.31 The parameters of such a lens are calculated as follows:

Given:

$$R_1 = -.125$$

$$n_2 = 1.88$$

The object distance from equation (83) is

$$s_1 = -(R_1 + R_1 n_2) = .360$$

The image distance of the first surface from equation (88) is

$$s_1' = R_1 + R_1/n_2 = -.1915$$

If a convenient minimum lens thickness, t, is -.0625, then from equations (90) and (93), the radius of the second surface is

$$s_2 = -(s_1' + t) = -R_2 = .2540$$

The image distance of the second surface (and of the lens), from equation (94), is

$$s_2' = R_2 = -.2540$$

The magnification from equation (99) is

$$m_L = 1/n_2 = .53$$

The exit half-angle from equation (104) is

$$\phi' = \sin^{-1}\left[\frac{1}{\pm\sqrt{1 + \frac{1}{n_2^2}}}\right] = 61^\circ\ 59'$$

Then the total angle of light output is

$$2\phi' = 123^\circ 58'$$

V-2.32 The total luminous intensity, I, of an Osram HBO-100 lamp is 350 lumens per steradian (total luminous flux equals 350 lumens per steradian x 4π steradians = 4,400 lumens) with a source diameter of .015". Consider that this source is placed to serve as object of this lens; then the solid angle of flux, ω , incident on the first surface of the lens, from equation (108) is

$$\omega = \frac{2\pi XY}{X^2} = \frac{2\pi Y}{X} = .736 \text{ steradians}$$

where

$$X = \sqrt{R_1^{\,2} + (R_1 n_2)^2} = .266$$

$$Y = X - R_1 n_2 = .031$$

The total flux input at the lens is

$$F = I\omega = 258 \text{ lumens}$$

Assuming no losses in the lens the total flux output of the lens is

$$F' = F = 258 \text{ lumens}$$

The solid angle of output of the lens, from (109), is

$$\omega' = \frac{2\pi X'Y'}{X'^2} = \frac{2\pi Y'}{X'} = 3.33 \text{ steradians}$$

where

$$X' = R_2 = .254$$

$$Y' = R_2 - R_2 \cos \phi' = .135$$

The luminous intensity of output is

$$I' = \frac{F'}{\omega'} = 77.3 \text{ candles}$$

This can be verified with equation (111).

The diameter of the virtual source formed by the lens is

$$(.015)(.53) = .008''$$

V-2.33 Actual measurements made with a lens of this design agree well with the calculated values, except that luminous intensity was approximately 20-25% lower than actual because of losses in the lens system by reflection and absorption.

V-2.34 Evaluation of the aplanatic negative meniscus lens relative to ideal point source requirements.

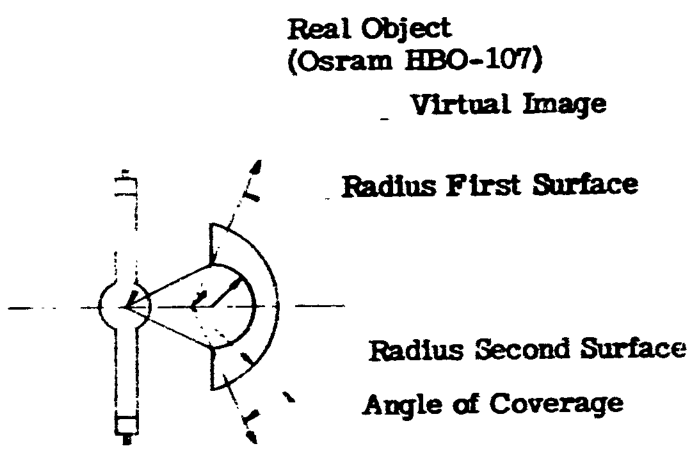
V-2.35 Theoretical calculations and experiments both prove that as the size of the source is optically reduced, the luminous intensity is also reduced. Hence, it can be seen that two major requirements of the ideal point source, minimum diameter with maximum luminous intensity, are inherently contradictory. In any particular instance, it is necessary to compromise these characteristics to achieve a satisfactory result. The size reduction achieved by the aplanatic negative meniscus lens is inversely proportional to the index of refraction of the lens material (equation 99). Therefore, in order to achieve a large size reduction, the lens material selected must have a high index of refraction. The luminance of the virtual image formed by the aplanatic negative meniscus lens is, under optimum conditions, equal to the luminance of the object (point source lamp) of the lens (equation 107). Since, by definition, luminance is the luminous intensity per unit of projected area, it can be seen that when the size of the point source object of the lens is reduced the luminous intensity is also reduced.

V-2.36 Theoretical and experimentally determined relationships between luminous intensity and source diameter are plotted in figure III-6 in Chapter 3. The experimental data was obtained using the Osram HBO-109 lamp as a source and a lens train consisting of spherical condensers, a microscope objective, and the experimental aplanatic negative meniscus lens discussed above (paragraphs V-2.29 to V-2.33). Data for the theoretical curve was computed from the maximum light available from the Osram HBO-109 lamp. Note that the theoretical luminous intensity of a given source diameter is always higher (by approximately 20%) than the luminous intensity actually produced by the lens train. This is explained by the fact that there is approximately 20-25% loss in the optical system by reflection and absorption in the lenses.

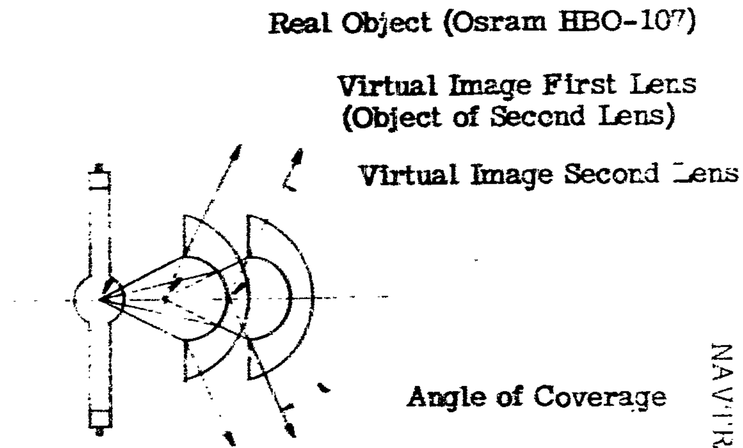
V-2.37 By using two identical meniscus lenses it is possible to further reduce the size of the actual point source, (figure V-4). However, this technique decreases the light output efficiency 40-60%. The virtual image of the first lens serves as the object of the second lens. For technical reasons as well as for economy the same lens material and design was used for both lenses. Figure V-5 shows the variation in luminous intensity and in source diameter for single and double meniscus lens systems when distance between the real source lamp and the first lens is varied. In the event that the use of different glasses and different internal radii is desired when compounding meniscus lenses, changes in the performance of the lens system must be anticipated.

V-2.38 The double meniscus lens system has a distinct effect on the resolution of the display-image. Figure V-6 shows the improvement obtained by compounding these lenses. However, it is important to note that this improvement occurs at point source to display-object distances less than 1.4". At point source to display-object distances greater than 1.4", diffraction effects come into play and the double meniscus lens system is inferior in resolution to the single lens system.

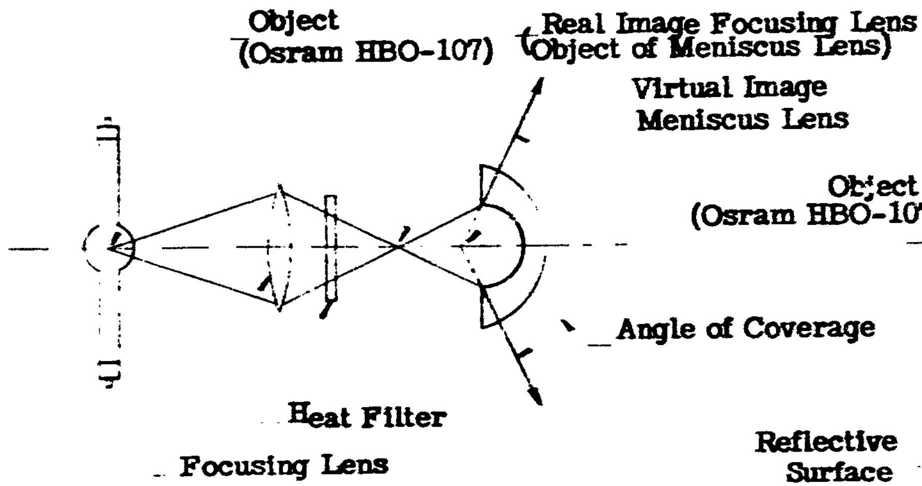
V-2.39 Angles of light output on the order of 180° to 200° are desired. For the aplanatic negative meniscus lens the angle of light output is a function of the index of refraction of the lens material (equation 104). The form of this relationship is such that for an index of refraction of 2, the angle of light output is 126°. Since existing lens materials have indexes less than 2, the angle of light output actually achieved is less than 126°. The angle of light output can be increased by deviating from the aplanatic meniscus lens condition as discussed in paragraph V-3.



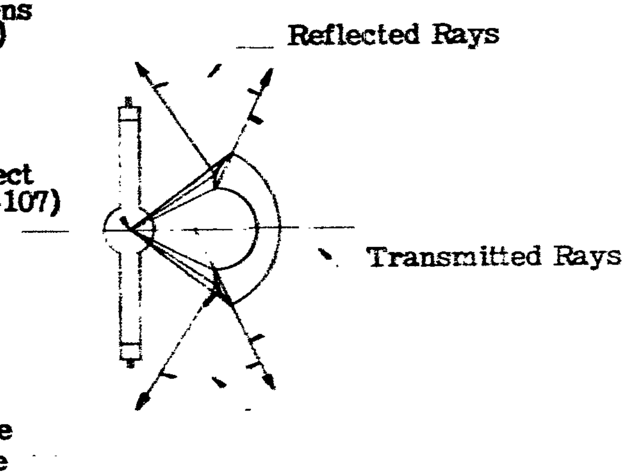
V-4a Single Meniscus Lens



V-4b Double Meniscus Lens



V-4c Auxiliary Lens System With Single Meniscus Lens



V-4d Single Meniscus Lens With Reflective Surface

Figure V - 4 - Schematics of Various Optical Arrangements for Reducing Source Diameter and Increasing Angle of Coverage.

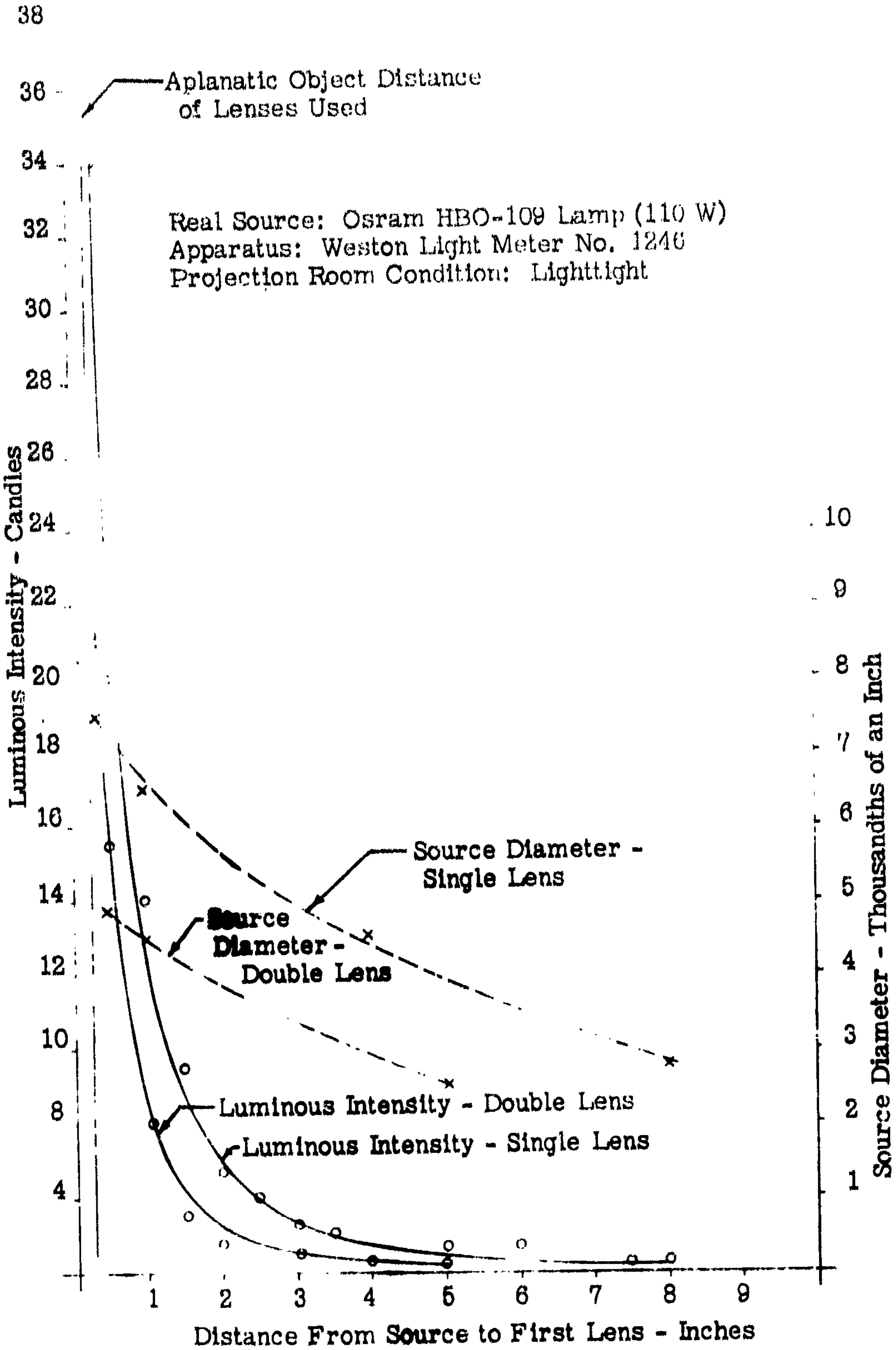


Figure V-5 - Variation in Source Diameter and Luminous Intensity With Real Source to First Lens Distance For Single and Double Meniscus Lens Systems.

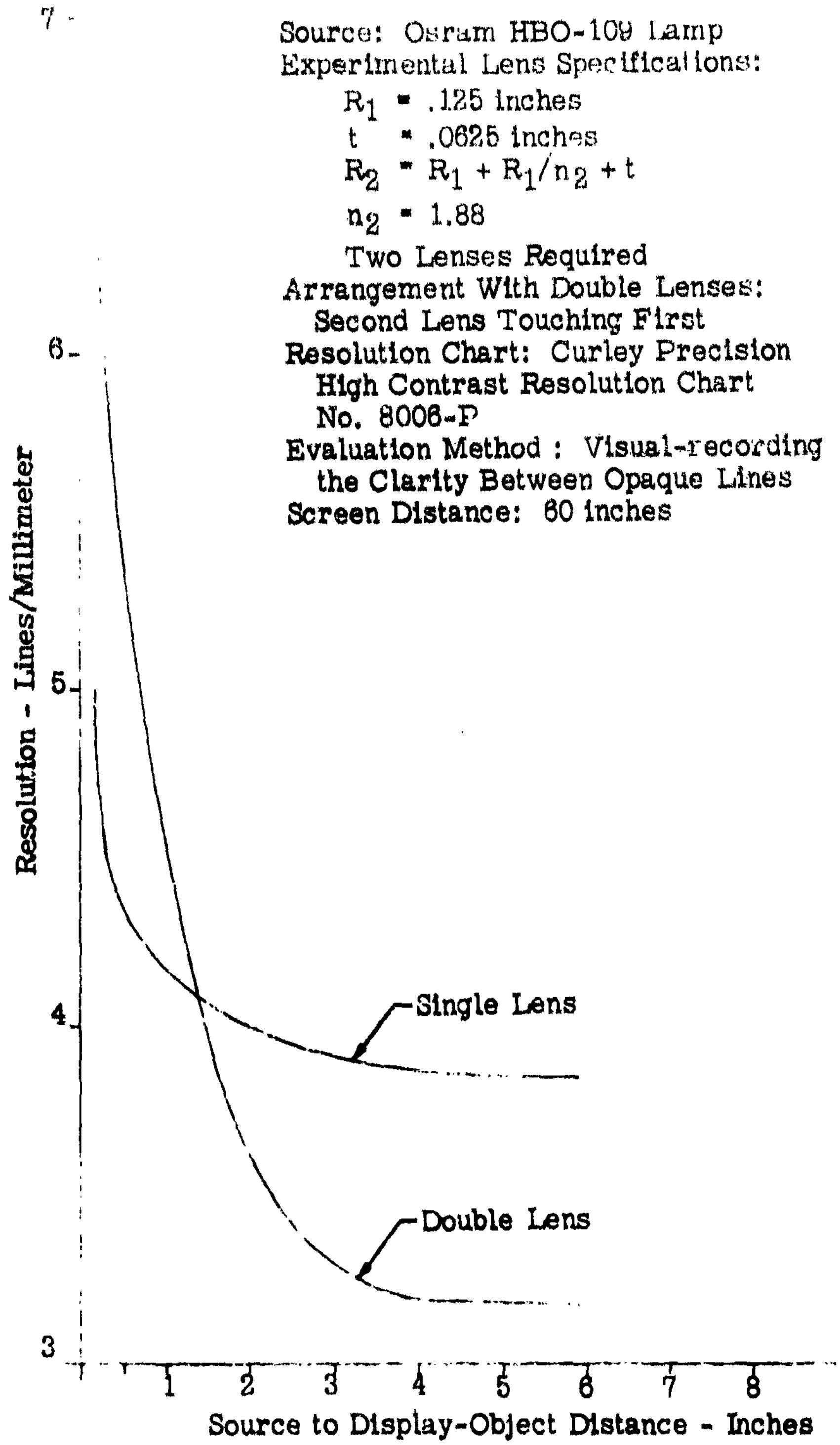


Figure V - 6 - Effect of Source to Display-Object Distance on Resolution for Single and Double Meniscus Lens Systems.

Another technique for increasing the angle of light output of the aplanatic negative meniscus lens is to apply a reflective coating to the back plane of the lens (figure V-4). This technique relies on the fact that when properly designed a reflective back surface of a meniscus lens will create a virtual image of the object (the actual point source) which will be very near the virtual image created through refraction by the lens. The reflected rays then appear to originate from the same point as the refracted rays. In addition, by properly crowning the back plane of the meniscus lens, it is possible to join the reflected rays at the periphery of the refracted rays. The final light output from such a lens is an uninterrupted portion of a sphere exceeding 180°. Of course the virtual source of the reflected rays is not demagnified as is the virtual source of the refracted rays. Therefore, the display-image produced by the reflected rays will be inferior in quality to that produced by the refracted rays. In some training tasks this condition is acceptable and the absence of peripheral vision is more harmful. Brightness of the reflected ray will equal the brightness of the refracted rays if the area of the reflected ring equals the area calculated from the internal radius of the meniscus lens. Where the areas are not equal illumination on the screen will vary sharply between the reflective and refracted light rays. Since, as the radii of the lens is made smaller the area of the reflective surface declines faster than the area calculated from the internal radius of the meniscus lens, there is a practical limit as to how small the meniscus lens may be made when using this technique.

V-2.40 The point source envelope is important to the extent that it limits the closeness to which the source may approach the display-object. With the aplanatic negative meniscus lens system, the projection source is the virtual image of the Osram HBO-109 lamp produced by the lens. The point source envelope is then the image distance of the lens and the image distance of this lens is equal to the radius of its second surface (equation 92). This in turn is limited only by the internal radius of the meniscus lens, the minimum practicable lens thickness, and the ability of very small lenses to transmit sufficient light.

V-2.41 Temperature of the meniscus lens, the effective point source envelope of this system, can be controlled and held to room temperature provided the point source lamp can be kept sufficiently far from the lens to prevent excessive heat transfer.

V-3 Other Lenses with a Large Angle of Light Output

V-3.1 Introduction to theory

V-3.2 In the previous sections of this appendix, it was shown that to achieve aplanatic conditions with a negative meniscus lens, a specific relationship between the object distance and the radius of the first surface must be maintained, in particular, the object distance must be equal to the radius of the first surface multiplied by the sum of one plus the index of refraction of the lens material. In addition, the curvature of the second surface must be centered at the image formed by the first surface. In the following sections two lens types, a plano-concave and a non-aplanatic negative meniscus lens, are evaluated. In paragraphs V-3.14 and V-3.23, the capabilities of these lenses as related to point source requirements are discussed.

V-3.3 The plano-concave lens

V-3.4 One weakness of the aplanatic negative meniscus lens is its limited angle of output. Analysis of this lens reveals that the angle of light output will be increased if the second surface of the lens is designed to further diverge the output of the first surface. If the second surface is a plane of sufficient extent to receive the output of the first surface until the angle of incidence of the rays striking the second surface equal or exceed the critical angle (total reflection), the angle of output will be 180°. In addition, through the use of a plane surface, economy of manufacture is obtained.

V-3.5 A theoretical analysis of such a plano-concave lens is made in paragraph V-3.8. This analysis reveals that if a point source of light serving as the object of a plano-concave lens is located at a distance $R_1 + n_2R_1$ from the concave first surface when this surface has a radius of curvature, R_1, and the lens has an index of refraction, n_2, then the lens will form a virtual image of the point source for each infinitesimal area of the second surface. The virtual image serving as a source for rays emerging from the lens at angle θ_2' will be distant $s_2' = -(s_2 \cos(\theta_2')) / \sqrt{n_2^2 - \sin^2\theta_2'}$ from the plane surface. (equation 120) It is further shown that these virtual images are smaller than the real point source object by a factor of $1/n_2^2$ (equation 116).

V-3.6 In paragraph V-3.10 it is shown that this lens is aplanatic and that aside from chromatism other aberrations effects are negligible.

V-3.7 In paragraphs V-3.9 and V-3.14 the theoretical and experimental characteristics of this lens are discussed.

V-3.8 Development of expressions for object distance and image distance and for lateral magnification

Consider in figure V-7 that rays from a point source of light are incident on a plano-concave lens having an index of refraction, n_2, and a radius of curvature of the first surface, R_1, located in air ($n_1 = 1$). If the point source object is located at a distance of $R_1 + R_1 n_2$ from the first surface then the following equations developed in paragraphs V-2.6 and V-2.7 apply to the first surface:

$$s_1 = -(R_1 + R_1 n_2) \qquad (83)$$

$$s_1' = R_1 + \frac{R_1}{n_2} \qquad (88)$$

$$m_1 = \frac{1}{n_2^2} \qquad (96)$$

If the second surface is a plane located to obtain a convenient minimum lens thickness, t, then the image formed by the first surface serves as the object of the second surface:

$$s_2 = -(s_1' + t) \qquad (112)$$

Snell's Law may be written for the second surface:

$$n_2 \sin i_2 = \sin r_2 \qquad (80a)$$

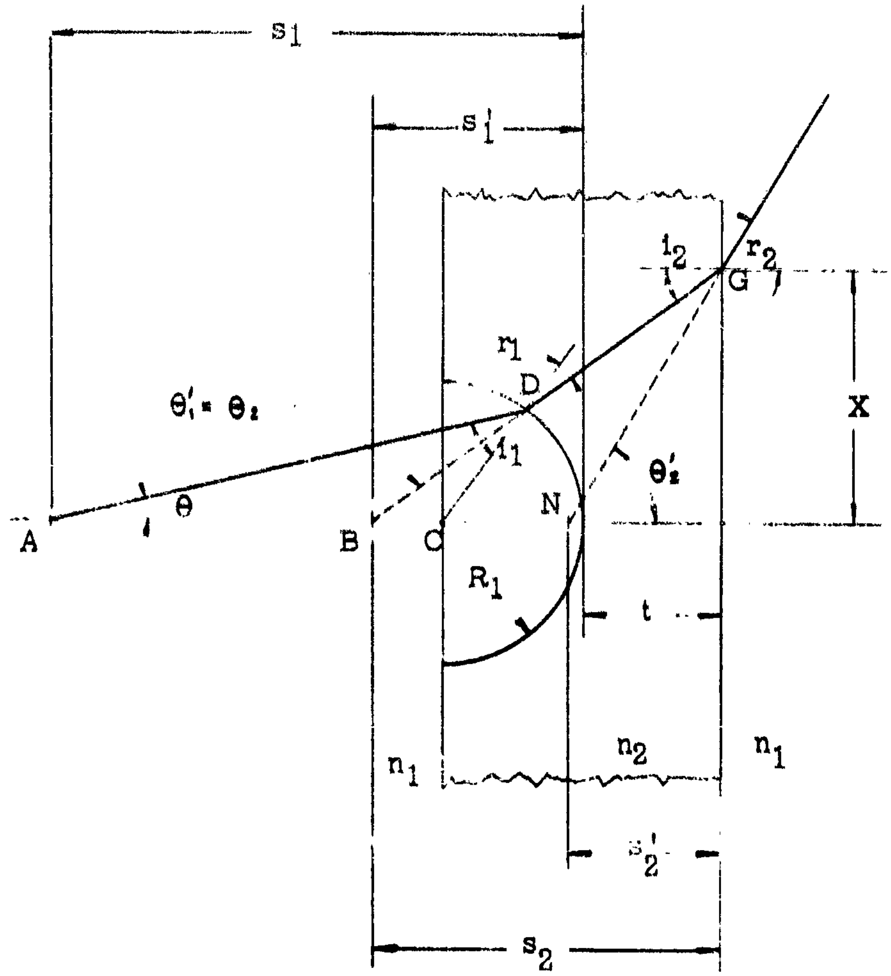


Figure V - 7 - Ray Tracing Diagram of Plano-Concave Lens.

From Abbe's Sine Condition, the magnification of the object of the second surface, m_2, is

$$m_2 = \frac{n_2 \sin \theta_2}{\sin \theta'_2} \qquad (97)$$

From the geometry of figure V-7, specific for the second surface

$$\theta_2 = i_2 \qquad (113)$$

$$\theta_2' = r_2 \qquad (114)$$

Therefore (80a) may be written

$$\frac{n_2 \sin\theta_2}{\sin\theta_2'} = 1$$

Substitute this in (97) above

$$m_2 = \frac{n_2 \sin\theta_2}{\sin\theta_2'} = 1 \qquad (115)$$

The lateral magnification of this lens, m_L, is the product of the magnifications of the surfaces:

$$m_L = m_1 m_2 = \frac{1}{n_2^2} \qquad (116)$$

From figure V-7, specific for the second surface

$$\sin \theta_2 = \frac{X}{\sqrt{s_2^2 + X^2}}$$

Solve this for X

$$X = \frac{s_2 \sin \theta_2}{\sqrt{1 - \sin^2 \theta_2}} \tag{117}$$

Substitute in this the value of $\sin \theta_2$ from (115)

$$X = \frac{s_2 \sin \theta_2'}{\sqrt{n_2^2 - \sin^2 \theta_2'}} \tag{118}$$

Also from figure V-7, specific for the second surface

$$\sin \theta_2' = \frac{X}{\sqrt{(-s_2')^2 + X^2}}$$

Solve this for X

$$X = \frac{-s_2' \sin \theta_2'}{\sqrt{1 - \sin^2 \theta_2'}} \tag{119}$$

Substitute in this the value of X from (118)

$$\frac{s_2 \sin \theta_2'}{\sqrt{n_2^2 - \sin^2 \theta_2}} = \frac{-s_2' \sin \theta_2'}{\sqrt{1 - \sin^2 \theta_2'}}$$

Solve this for s_2' and substitute the trigonometric identity $\cos^2 \theta_2' = 1 - \sin^2 \theta_2'$

$$s_2' = - \frac{s_2 \cos \theta_2'}{\sqrt{n_2^2 - \sin^2 \theta_2'}} \tag{120}$$

If the value for X from (117) is substituted in (119)

$$\frac{s_2 \sin\theta_2}{\sqrt{1 - \sin^2\theta_2}} = \frac{-s_2' \sin\theta_2'}{\sqrt{1 - \sin^2\theta_2'}}$$

and if this is solved for s_2'

$$s_2' = - \frac{s_2 \sin\theta_2 \sqrt{1 - \sin^2\theta_2'}}{\sqrt{1 - \sin^2\theta_2} \left(\sin\theta_2'\right)} \tag{121}$$

Remembering the trigonometric identities

$$1 - \sin^2 Y = \cos^2 Y$$

$$\sin Y/\cos Y = \tan Y$$

(121) becomes

$$s_2' = - s_2 \frac{\tan\theta_2}{\tan\theta_2'} \tag{122}$$

V-3.9 Note in (120) that as θ_2' approaches 0, s_2' approaches $-s_2/n_2$ and that as θ_2' approaches 90°, s_2' approaches 0. Now expression (122) means that for each value of the slope angle of the incident rays θ_2 there is a corresponding and unique value of the slope angle of the refracted rays θ_2'. These refracted rays will appear to originate from a point source at a unique point distant s_2' from the second surface when the object of the second surface is the virtual image of the point source formed by the first surface at distance s_2 from the second surface. Expression (120) shows that distance s_2' is indeed unique for each value of θ_2'. Physically, this means that the rays emerging from this lens at each value of θ_2' originate from a different virtual point source and the luminous intensity of any one of these virtual point sources will be determined by the luminous flux incident on that portion of the second surface which forms it.

V-3.10 Evaluation of aberrations for the plano-concave lens

V-3.11 Recalling from V-2.12 the requirements for freedom from spherical aberration, it can be seen that the first surface of the plano-concave lens is free from spherical aberration. Because the second surface is a plane, it too is free from spherical aberration.

V-3.12 It can easily be shown from equations (95), (96) and (115) that the condition for freedom from coma, namely, $\sin\theta_1/\sin\theta_2'$ constant for all values of θ_1 is also maintained. Therefore this lens is also aplanatic.

V-3.13 Chromatism is similar to that discussed in paragraph V-2.18 above. The effects of other aberrations are negligible since the object of the lens in this problem is essentially a point and lies on or very near the optical axis.

V-3.14 Experimental evaluations of a plano-concave lens.

V-3.15 Experimental evaluation of a plano-concave lens like that discussed above shows that the light output in any direction θ_2' follows closely the cosine of θ_2'. Hence, though a 180° angle of output

is theoretically possible, the light output near the edges of this hemisphere is extremely low.

V-3.16 As explained in paragraph V-3.9, this lens does not form the virtual image of the point source at one particular point for the entire output cone of light; on the contrary, rays at each individual slope angle θ_2 form a virtual source of the initial object. However, each of these sources radiate in only one direction, the direction θ_2' corresponding to θ_2 in (122). Therefore, the effective point source used for projection consists of a unique source for each direction of projection θ_2'.

V-3.17 The non-aplanatic negative meniscus lens

V-3.18 As noted, the angle of light output of an aplanatic negative meniscus lens is a function of the index of refraction of the lens material and is independent of the lens dimensions (equation 104). This is also the case with magnification (equation 99). However, the angle of light output and the magnification can be changed if the point source object of the lens is shifted from the aplanatic point where $s_1 = -R_1(1 + n_2)$.

V-3.19 In paragraph V-3.22 it is shown that the image distance s_2' varies with the object distance s_1 in accordance with the following expressions:

$$s_1' = R_1 \left[1 + \tan \sin^{-1} \frac{1}{n_2} \left(\frac{s_1 + R_1}{\sqrt{(s_1 + R_1)^2 + R_1^2}} \right) \right] \qquad (126)$$

$$s_2 = -(s_1' + t) \qquad (90)$$

$$s_2' = -s_2 \qquad (94a)$$

In (126) as s_1 increases s_1' increases but at a slower rate. Thus as the point source object is shifted away from the aplanatic object point, the

image is shifted away from the aplanatic image point in the same direction.

V-3.20 In paragraph V-3.22 it is shown that the magnification by this lens is $n_2(R_1 - s_1') / R_1 + s_1$ (equation 129). From this it is evident that as s_1 increases the magnification decreases and therefore the amount of reduction increases.

V-3.21 In paragraph V-3.23 the theoretical and experimental characteristics of this lens are discussed.

V-3.22 Development of expressions for object distance, image distance and magnification for the non-aplanatic negative meniscus lens.

Consider in figure V-8 the ray $\overline{AM}$ from the point object to the extreme edge of the first surface of a negative meniscus lens. If the lens is in air and has an index of refraction, n_2, Snell's Law may be written

$$\sin i_1 = n_2 \sin r_1 \tag{80}$$

From figure V-8 for ray $\overline{AM}$

$$\sin i_1 = \frac{s_1 - R_1}{\sqrt{(s_1 - R_1)^2 + R_1^2}}$$

Recalling that, by convention, R_1 and i_1 are negative, make this explicit for the first surface

$$-\sin i_1 = \frac{s_1 + R_1}{\sqrt{(s_1 + R_1)^2 + R_1^2}} \tag{123}$$

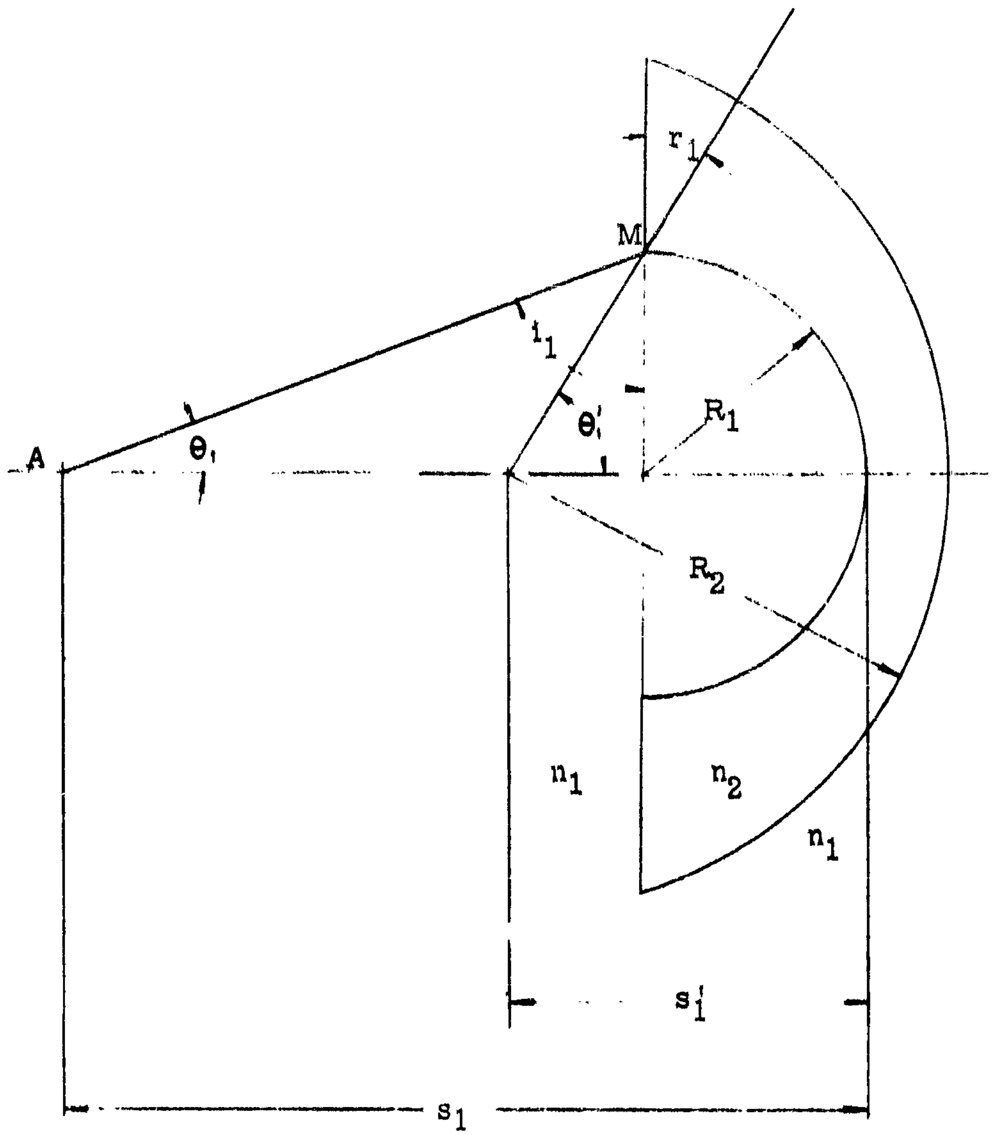


Figure V - 8 - Ray Tracing Diagram of Non-Aplanatic Negative Meniscus Lens.

Substitute this in (80)

$$- \sin r_1 = \frac{1}{n_2} \left(\frac{s_1 + R_1}{\sqrt{(s_1 + R_1)^2 + R_1^2}} \right) \tag{124}$$

From figure V-8

$$\tan r_1 = \frac{s_1' - R_1}{R_1}$$

Recalling that, by convention, r_1, s_1' and R_1 are negative, make this explicit for the first surface:

$$- \tan r_1 = \frac{-s_1' + R_1}{-R_1} \tag{125}$$

Solve for s_1'

$$s_1' = R_1 (1 - \tan r_1) \tag{125a}$$

Substitute (124) in this

$$s_1' = R_1 \left[1 + \tan \sin^{-1} \frac{1}{n_2} \left(\frac{s_1 + R_1}{\sqrt{(s_1 + R_1)^2 + R_1^2}} \right) \right] \tag{126}$$

Select the radius of the second surface, R_2, in the same manner as is done for the aplanatic negative meniscus lens:

$$s_2 = -(s_1' + t) = -R_2 \qquad (90)(92)$$

$$s_2' = R_2 \tag{94}$$

From Abbe's Sine Condition, the magnification of the object by the first surface, m_1, is

$$m_1 = \frac{\sin \theta_1}{n_2 \sin \theta_1'} \tag{95}$$

Recall that (81a) and (87a) apply to any negative meniscus lens:

$$\sin \theta_1 = \frac{R_1}{s_1 + R_1} \sin i_1 \tag{81b}$$

$$\sin \theta_1' = \frac{R_1}{R_1 - s_1'} \sin r_1 \tag{87b}$$

Divide (81b) by (87b)

$$\frac{\sin \theta_1}{\sin \theta_1'} = \left(\frac{R_1 - s_1'}{s_1 + R_1}\right) \frac{\sin i_1}{\sin r_1}$$

Substitute $\sin i_1 / \sin r_1$ from (80) in this:

$$\frac{\sin \theta_1}{\sin \theta_1'} = \frac{R_1 - s_1'}{s_1 + R_1} n_2 \tag{127}$$

Substitute this in (95)

$$m_1 = \frac{R_1 - s_1'}{R_1 + s_1} \tag{128}$$

For the second surface, (98) applies

$$m_2 = n_2 \tag{98}$$

Therefore the lateral magnification of this lens, m_L, is

$$m_L = m_1 m_2 = \frac{R_1 - s_1'}{R_1 + s_1} \; n_2 \tag{129}$$

Remember that $\theta_1' = \theta_2 = \theta_2'$, substitute (127) in (129)

$$m_L = \frac{\sin \theta_1}{\sin \theta_2'} \tag{129a}$$

V-3.23 Experimental evaluation of the non-aplanatic negative meniscus lens.

A non-aplanatic negative meniscus lens was fabricated in accordance with the design shown in figure V-9. Experiments with this lens included the measurement of virtual source diameter, angular output and luminous intensity with this lens. Projection using the virtual source formed by this lens proved satisfactory despite the slight increase in aberrations. One minor difficulty was encountered. The intensity of light declines from a maximum at the optical axis to a minimum at the fringe of the cone of output approximately proportionally with the cosine of the angle. Experiments with the aplanatic negative meniscus lens indicated that intensity with this lens was quite constant over the entire cone of light output.

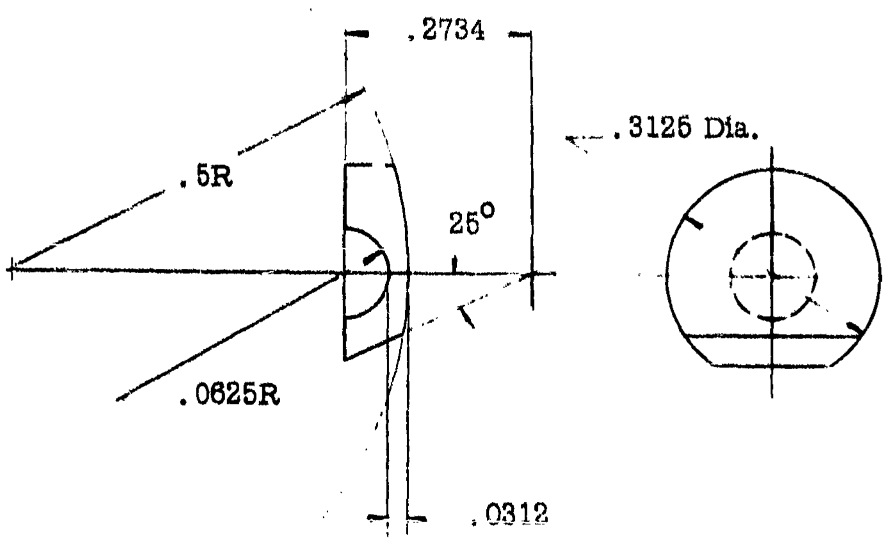


Figure V-9 - Design of a Non-Aplanatic Negative Meniscus Lens.

V-4 Design Considerations

V-4.1 The material for these experimental lenses is a rare earth element glass manufactured by the Eastman Kodak Company (EK-448). In the investigation of existing high refractive index glasses the following characteristics were considered; clarity, absence of color tints and capability to withstand high temperatures and severe temperature gradients. In addition, the lens material should not favor chromatic aberrations. EK-448 was chosen primarily for its high refractive index (1.8804) and clarity. It has the disadvantage of being a "heat free" glass (not capable of withstanding high temperatures). Slight chromatic aberrations are inherent within the material; however, the effect is negligible due to the small separation between the two extreme visible wavelengths which are the 0.00004 cm. wave and the .00007 cm. wave. The separation involved is approximately .002" which is smaller than the anticipated source diameter. Tests have not revealed deleterious aberration effect to the naked eye. Rare earth element materials are normally non-absorbent to the visual rays from 400 microns to 200 microns with visual ray absorption not exceeding 2% per cm. of thickness.

V-4.2 High refractive index is a necessary requirement because the higher the refractive index, the smaller the R_1/n_2 value, that is, the distance that the center of the output cone is displaced from the back plane of the meniscus lens. The smaller this R_1/n_2 value, the greater the angle of light output.

V-4.3 The axial alignment of any lens system is very important. It assures more uniform flux distribution and a greater reduction of the source. Care must be taken to avoid a temperature gradient in the chosen glass material (EK-448). Cooling the glass and lamp combination is harmful to the latter since the cooling effect lowers the light output as well as increases the source diameter of the HBO-109.

V-4.4 Experimentally many by-products of the initial negative meniscus lens have been evaluated. A single meniscus lens was designed (see figure V-9) and experiments conducted. One of the experiments was to place the negative meniscus lens at the pre-determined distance and evaluate the effectiveness of the equations. Other tests on this lens evaluated light efficiency, effect of aberration, effect of extreme heat, and the resolving power of the final point source.

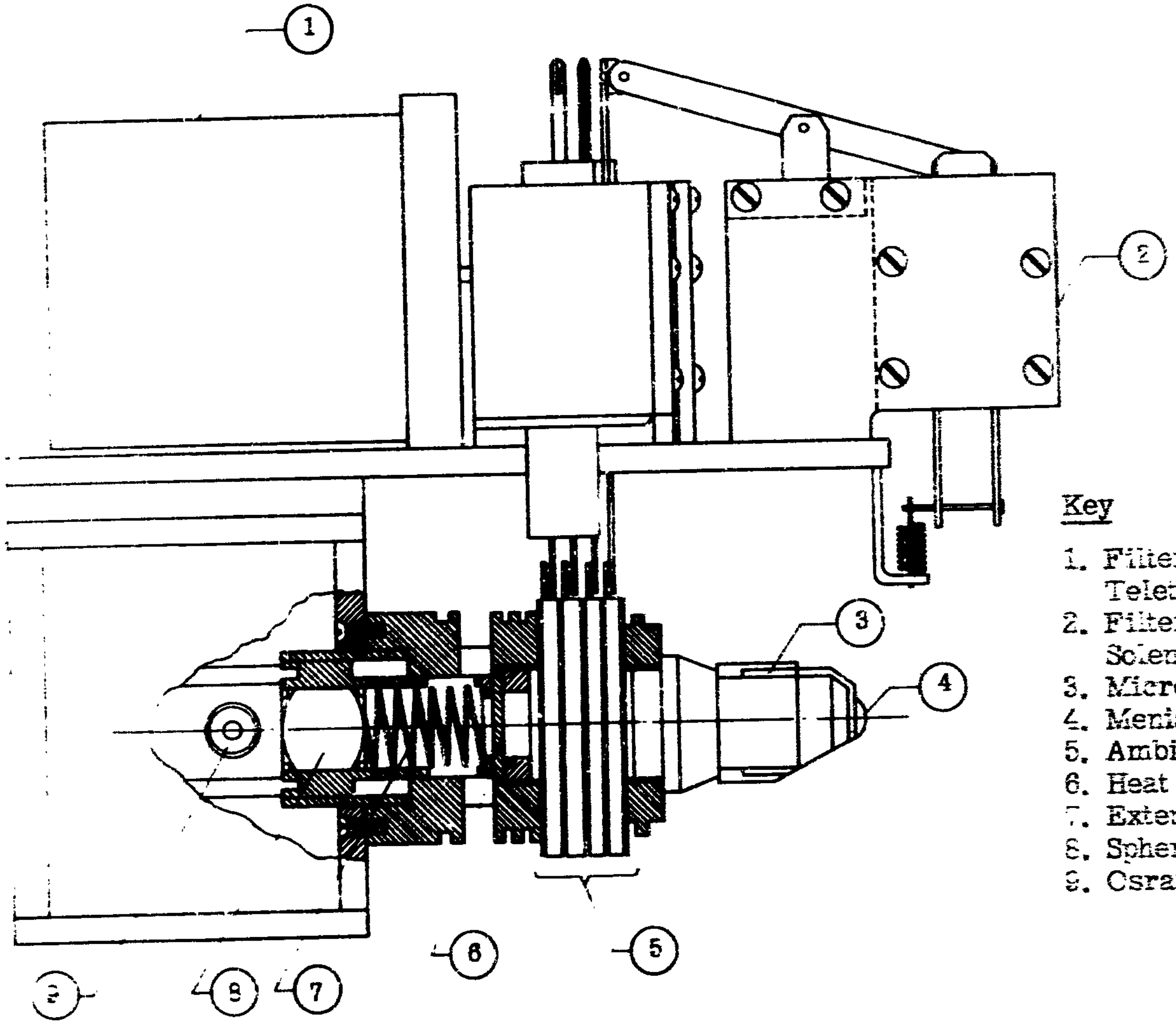
V-4.5 Point Source Assembly

V-4.6 To simulate touchdown conditions on a specific helicopter a complete point source assembly was designed and fabricated. The following are the specifications for this design:

a) a point source device to simulate touchdown conditions where the distance between the pilot's eye and the earth is 12'.
b) the final lens element touching the transparency to be at room temperature.
c) capable of projecting over 180°.
d) the final point source to be approximately .004" in dia.
e) light output to be in the vicinity of 30 candles.
f) capable of simulating ambient light characteristics.

V-4.7 To simulate touchdown at a distance of 12' with an assumed transparency scale ratio of 2,000 : 1, point source to outer glass envelope distance must be .072"; consequently a very small negative meniscus lens had to be utilized as the final lens element. To achieve the specified angular coverage it was necessary to use a non-aplanatic meniscus lens. It was further necessary to cut the bottom section of the lens to assure the .072" required for touchdown simulation. This cutting away of the lens does not affect the projection since rays emitting from that section are blocked from the screen by the helicopter cockpit. The entire point source assembly was angled 25° from the horizontal in order to utilize the central portion of the negative meniscus lens to project on a specific part of the screen most viewed by the pilot.

V-4.8 Figure V-10 shows the point source assembly designed to satisfy the above specifications. The device consists of the HBO-109 mercury vapor lamp positioned horizontally in order to minimize the height of the device. The spherical condenser shown in the diagram is fabricated out of quartz in order to withstand the high temperatures encountered in the system. No heat filter is used between the Osram and the condenser since all available heat filter materials break as soon as the Osram lamp reaches operating temperature. The purpose of this condenser is to intercept part of the light flux radiating from the Osram lamp and collimate these rays for insertion into the microscope objective. The light flux is collimated prior to entering the objective



Key

1. Filter Control Teletorque
2. Filter Control Solenoids
3. Microscope Objective
4. Meniscus Lens
5. Ambient Light Filters
6. Heat Filter
7. Extension Spring
8. Spherical Condenser
9. Osram HBO-109 Lamp

Figure V-10 Drawing of de Florez Point Light Source, Model III

because it has been found desirable to insert filters within this collimated path rather than in any other section of the device.

V-4.9 The purpose of the heat filter is to protect ambient light filters and the microscope objective since heat can only damage those items rather than the condenser. The objective used in this design is capable of withstanding approximately 125°F. Higher temperatures tend to soften and distort the bonding material used between lenses. The sole purpose of the microscope objective is to reconverge the collimated beam input; this, of course, is a necessary condition for the meniscus lens. All lenses and filters with the exception of the condenser have been coated to minimize the light losses due to the optical elements, since 12 air to glass surfaces exist at which light losses can take place.

V-4.10 This experimental point source assembly was tested for durability, light efficiency, resolution and angular output. It has been found satisfactory on all accounts. The resolution of this unit has been measured at approximately 6 lines per mm. It produces a point source approximately .0045" in diameter with a light output of about 30 candles.

APPENDIX VI

TABULATION OF PLASTIC MATERIALS

Name	Manufacturer	Chemical Family	Size - Max.
Lumirth L. 828 flexible	Celanese	Cellulose Acetate	41.5" x 3.75" 20" x 50" 25" x 40"
Kodapak I F - 122 flexible	Eastman Kodak	Cellulose Acetate	40" wide 20" x 50" 25" x 40"
Kodapak II F - 290 flexible	Eastman Kodak	Cellulose Acetate Butyrate	40" wide 20" x 50" 25" x 40"
Kodak IV 401 flexible	Eastman Kodak	Cellulose Triacetate	40" wide 20" x 50" 25" x 40"
Plexiglas II UVA MIL - P - 5425B rigid	Rohme & Haas	Acrylic	100" x 120"
Enduron CR - 39 rigid	Pioneer Scientific Corp	Allyl Base Co-pollymer	48" x 48"
Mylar 300 500 750 flexible	Du Pont	Polyethylene Terephthalate	52" wide
Plastecele semi-flexible	Du Pont	Cellulose Acetate	20" x 50"

TABULATION OF PLASTIC MATERIALS (Cont'd)

Name	Thickness Min.	Thickness Max.	Packaging Rolls	Packaging Sheets	Method of Producing
Lumirth L. 828 flexible	.003"	.020"	x	x	Cast
Kodapak I F - 122 flexible	.005"	.020"	x	x	Cast
Kodapak II F - 290 flexible	.001"	.002"	x	x	Cast
Kodapak IV 401 flexible	.003"	.015"	x	x	Cast
Plexiglas II UVA MIL - P - 547 rigid	.060"	1.0"		x	Cast
Enduron CR - 39 rigid	.031"	1.0"		x	Cast
Mylar 300 500 750 flexible	.003"	.0075"	x	x	
Plastecele semi-flexible	.020"	1.0"	x		Compression molding

TABULATION OF PLASTIC MATERIALS (Cont'd)

Name	Refractive Index (N_D)	% Transmission of White Light (catalogue)	Average Modulus of Elasticity x 10^5
Lumirth L. 828 flexible	1.496	86-93	50% RH - 2.7
Kodapak I F - 122 flexible	1.29	90	3 - 4 T
Kodapak II F - 290 flexible	1.19	92	2 - 2.5 T
Kodak IV 401 flexible	1.29	90	3.5 - 4.5 T
Plexiglas II UVA MIL - P - 5425B rigid	1.49	92	4.25
Enduron CR - 39 rigid	1.503	90-92	2 - 3C
Mylar 300 500 750 flexible	1.64		5 T
Plastecele semi-flexible	1.5	87	2

NOTE: All plastic materials are very clear, free of dye marks and striations.

W Wide
T Tension
C Compression
RH Relative Humidity

PLASTIC MATERIALS TESTED AND FOUND UNSATISFACTORY*

Pliofilm

Clopane

Cellulose nitrate

Polyflex I & II

Methaflex

Vinylite

Krene

Visqueen

* T[illegible] materials were found wanting in one or more of the following properties:

a. Optical clarity
b. Tensile strength
c. Shear strength
d. Tearability
e. Modulus of Elasticity
f. Creep strength.

APPENDIX VII

Tabulations of Inks, Dyes and Lacquers

VII-1 Tabulation of Inks (tested on cellulose acetate)

	Brush	Speed Ball Pen	Air Brush	Remover	Blendability
S & V T-26699	V.G. Little spreading	V.G. Little spreading	F. Tends to opaque slightly	Ethyl Alcohol	1. F. by spraying 2. P. with brush 3. P. by dipping
S & V T-26744	G. Spreads at edges	G. Little spreading	P. Tends to opaque	Ethyl Alcohol	P. Can be blended slightly by over spraying
S & V T-26870	F.	G. Little spreading	P. Tends to opaque slightly	Ethyl Alcohol	P. Can be blended slightly by over spraying
S & V T-26871	F.	G. Little spreading	P. Tends to opaque slightly	Ethyl Alcohol	P. Can be blended slightly by over spraying
S & V T-26872	G.	F. Little Spreading	P. Tends to opaque slightly	Ethyl Alcohol	P. Can be blended slightly by over spraying

VII-1 Tabulation of Inks (Cont'd.)

	Brush	Speed Ball Pen	Air Brush	Remover	Blendability
*C & D Regular (filtered)	V.G. Spreads at edges	F. Spreads on contact	F. Tends to opaque Transparency possible to achieve by flooding	C & D cleanser	P. can be blended by spreading with finger
*C & D A-080155	V.G.	P.	G.	C & D cleanser	P. could be blended slightly by over spraying
=Artone	V.G.	V.G. Must be applied very fast	G. Must be diluted with 1 part - Artone ink 1 part - Amyl acetate 1 part - Ethyl acetate	Amyl or Ethyl Acetate	G. could be blended slightly by over spraying
S & V T-24004 B-5510	For Spray Only		V.G.	Ethyl Alcohol	F. by spraying

= Masking tape method satisfactorily used on cellulose acetate and plexiglas
* Requires long time to dry

V.G. - Very good
G. - Good
F. - Fair
P. - Poor

S & V - Sinclair & Valentine
C & D - Cushman & Denison

VII-2 Tabulation Of Dyes and Lacquers
(Tested on Cellulose Acetate and Plexiglas)

Dyes & Lacquers	General Information	Brush	Dipping	Spraying	Blendability	Removers
REZ-N-DYE Schwartz Chemical Co.	Note A	G.	V.G.	F.	V.G. by spray or brush	not removable
ALCOHOL PLASTIC DYES(cold dip) Beron Plastic, Inc.	Note A	G.	V.G.	F.	V.G. by spray or brush	not removable
REZ-N-DYE (concentrate) (light jade) Schwartz Chem Co.	Note E	G.	G.	G.	P.	not removable
AIR BRUSH (concentrate) Schwartz Chem Co.		G.	G.	G.	P.	not removable
REZ-N-LAC (concentrate) Schwartz Chem Co.	Note C	G.	G.	F.	P.	REZ-N-CLEAN
REZ-N-LAC (concentrate) #1. Schwartz ChemCo.	Note D	G.	G.	G.	P.	REZ-N-CLEAN
REZ-N-COATING (AT 25) Schwartz ChemCo.	Note B	G.	G.	G.	P.	Amyl Acetate or thinner

VII-2 Tabulation Of Dyes and Lacquers (Cont'd.)

NOTES:

A: 1. must be rinsed with water after each application.
2. for best results dye must be fresh.
3. slow acting dyes can be reactivated by adding concentrated dye in following proportions: 2 oz. fresh dye to one gallon old dye.

B: 1. it is supplied in concentrate form and various densities of color.
2. can be diluted with thinner.

C: 1. can be diluted as follows: 1 part REZ-N-LAC
1 part REZ-N-LAC clear
2 parts REZ-N-LAC thinner

2. lacquer tends to peel.

D: Has the tendency to "run" unevenly when used full strength. Can be diluted as follows: 1 part concentrate #5, 2 parts Methyl Alcohol

E: Can be used full strength or can be diluted as follows: 1 part concentrate, 2 parts Methanol

F: All dyes and lacquers could be applied several times for desired density.

SYMBOLS:

V.G. - Very good	F. - Fair
G. - Good	P. - Poor

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